PARTIAL NITRIFICATION OF HIGH NITROGEN WASTEWATER IN THE CONTACT STABILIZATION PROCESS

BY

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To my Father-in-law,
The late Sun-How Chung

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TABLE OF CONTENTS

page

ACKNOWLEDGEMENTS iii

ABSTRACT vii

CHAPTERS

1 INTRODUCTION 1

2. LITERATURE REVIEW 4

Microbiology 4
Stoichiometry 5
The Maximum Specific Growth Rates and Half-Saturation Coefficients for Nitrosomonas and Nitrobacter 7
Kinetics and Models in Nitrification 10
Nitrite Build-up in Nitrification 15
Nitrification in Contact Stabilization Process ... 17

3. DETERMINATION OF AMMONIA AND NITRITE HALF-SATURATION COEFFICIENTS FOR NITRIFICATION 19

Introduction 19
Development of an Expression for Measurement of K_{NH4A} and K_{NO2A} Using Fed-Batch Cultures 19
Materials and Methods 24
  Summary of Experiments 24
  Microorganisms 24
  Experimental Procedures 24
  Analytical Methods 28
    Ammonia Nitrogen 28
    Mixed Liquor Suspended Solids 30
    Nitrite and Nitrate Nitrogen 30
  Results of Experiments 31

4. DETERMINATION OF THE EFFECTIVE MAXIMUM SPECIFIC GROWTH RATE OF NITROGEN OXIDIZING BACTERIA..... 40

Introduction.. 40
Basis for the Determination of $\hat{\mu}_A - b_A$ Using a Batch Culture.............................. 41
Materials and Methods........................... 44
  Summary of Experiments........................ 44
  Microorganisms................................ 44
  Experimental Procedures....................... 44
  Analytical Methods............................ 45
    Ammonia Nitrogen............................ 45
    Nitrite and Nitrate Nitrogen................ 45
    Mixed Liquor Suspended Solids............... 45
  Results of Experiments........................ 45

5. CONTROL OF NITRIFICATION IN CONTACT STABILIZATION PROCESS.......................... 53

Introduction.. 53
Materials and Methods........................... 54
  Microorganisms................................ 54
  Synthetic Wastewater.......................... 54
Experimental Procedures......................... 55
  Analytical Methods............................ 61
    Ammonia Nitrogen............................ 61
    Nitrite and Nitrate Nitrogen................ 62
    Mixed Liquor Suspended Solids............... 62
    Chemical Oxygen Demand...................... 62
    Total Kjeldahl Nitrogen..................... 62
  Results of Experiments........................ 64

6. MODEL DEVELOPMENT AND COMPUTER SIMULATION........ 67

Introduction.. 67
Model Matrix.. 68
  Oxygen Utilization by Autotrophs.............. 72
  Nitrate Utilization Production and Utilization, Alkalinity Production by Heterotrophs Growing under Anoxic Conditions (coefficients 9,3; 14,3; 14,4; 13,4)........................... 72
Model Components................................ 74

Model Processes................................. 75
  Aerobic Growth of Nitrate Reducing Heterotrophs................................ 75
  Aerobic Growth of Nitrite Reducing Heterotrophs................................ 75
  Anoxic Growth of Nitrate Reducing Heterotrophs................................ 76
  Anoxic Growth of Nitrite Reducing Heterotrophs................................ 76

Growth of Ammonia Oxidizers.................... 77
Growth of Nitrite Oxidizers.................... 77
Decay of Nitrate Reducing Heterotrophs.......... 77
Decay of Heterotrophic Nitrite Denitrifiers.... 78
Decay of Ammonia Oxidizers..................... 78
Decay of Nitrite Oxidizers..................... 78
Ammonification of Soluble Organic Nitrogen..... 78
Hydrolysis of Entrapped Organics............... 79
Hydrolysis of Entrapped Organic Nitrogen....... 79
Stoichiometric Model Parameters.................... 79
Kinetic Model Parameters........................... 82
Stoichiometric Coefficients........................ 86
Coefficient $v_{16,5}$ and $v_{16,6}$...................... 87
Coefficient $v_{12,3}$ and $v_{12,6}$...................... 87
Coefficient $v_{15,1}$ and $v_{15,11}$...................... 87
Coefficient $v_{11,3}$ and $v_{11,4}$...................... 88
Computer Simulation Results........................ 88

7. EVALUATION OF THE PROPOSED MODEL................. 91

Introduction....................................... 91
Statistical Analysis of Experiment and Simulation Data in Contact Stabilization Process........... 91
Simualtion of Fed-Batch Experiments............... 99

8. CONCLUSIONS..................................... 104

APPENDICES

A. EXPERIMENT DATA................................. 106

B. COMPUTER PROGRAM................................ 118

C. EXPERIMENT AND SIMULATION GRAPHS................ 127

REFERENCES... 134

BIOGRAPHICAL SKETCH................................ 139

Abstract of Dissertation Presented to the Graduate School
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PARTIAL NITRIFICATION OF HIGH NITROGEN WASTEWATER IN THE CONTACT STABILIZATION PROCESS

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August 1992

Chair: Ben Koopman
Major Department: Environmental Engineering Sciences

The purpose of this research was to evaluate the effect of solids retention time (SRT) and sludge recycle rate on nitrification of high-nitrogen wastewater in the contact stabilization process, and to develop and verify a computer model that depicts the transformation of nitrite as well as other nitrogen forms in wastewater treatment processes.

A bench-scale contact stabilization process was operated at a temperature of 25°C with a feed of synthetic wastewater containing 230 g/m^3 ammonia nitrogen. SRT, over a range of 4.8 to 8 days, had little effect on the proportion of effluent nitrogen which was present in an oxidized form, but had a significant effect on the relative concentrations of nitrite and nitrate nitrogen. Higher nitrite concentrations were observed at low SRT. Sludge recycle rate had a large effect on the proportion of effluent nitrogen in oxidized forms and substantially influenced the relative concentrations of nitrite and nitrate at low SRT. The proportion of oxidized nitrogen in process effluent varied from 10% to 65% of total nitrogen when the sludge recycle rate was controlled between 20% and 140% of influent flow rate. At an SRT of 4.8 days, nitrite varied from 12% to 5% of the total oxidized nitrogen as the sludge recycle ratio was controlled between 50% and 110%. At higher SRTs, nitrite was low (3% or less of total nitrogen) and did not vary with sludge recycle ratio.

A computer model for the contact stabilization process was developed using rate expressions from the Activated Sludge Model No. 1 proposed by the International Association on Water Pollution Research and Control (IAWPRC). New rate expressions for reactions involving nitrite were added to the IAWPRC model. Ammonia and nitrite half-saturation coefficients and effective maximum specific growth rates for ammonia oxidizing and nitrite oxidizing biomass in synthetic wastewater were determined experimentally, while values for the other biokinetic and stoichiometric model parameters were taken from the literature. The computer model gave predictions for total oxidized nitrogen that were very close (± 6% on the average) to experimental results, but tended to underpredict nitrite concentrations.

CHAPTER 1

INTRODUCTION

Nitrogen removal from municipal and industrial wastewaters is becoming increasingly important. The most cost-effective means of nitrogen removal usually consists of biological nitrification (the oxidation of ammonia to nitrate) followed by biological denitrification (the reduction of nitrate to gaseous end products). Frequently, activated sludge processes are applied because they can be configured to utilize the organic compounds present in influent wastewater as electron donors for denitrification.

Invariably, activated sludge systems utilized for nitrogen removal are designed to achieve "complete nitrification" of influent wastewater. This is true even when only partial nitrogen removal is required, much of the reason for this practice lies in the biokinetics of nitrifier growth, which in most activated sludge process configurations, makes nitrification on "all or none" phenomenon. Operation is stable in a non-nitrifying mode or in a fully nitrifying mode. In between, problems are experienced due to the accumulation of a nitrification intermediate--nitrite--which leads to erratic chlorine demand, rising sludge, and effluent toxicity.

Gujer and Jenkins (1975) were the first to suggest that the contact stabilization process could be used to achieve partial nitrification. They developed a mathematical model for the process that showed the rate of sludge recycle to have a large effect on the extent of nitrification. Alexander et al. (1980) confirmed the capacity of the contact stabilization process for partial nitrification.

Since nitrification is an energy-intensive process and is also a significant determinant of reactor volume requirements in activated sludge processes, it is, in fact, wasteful to design for complete nitrification when only partial nitrogen removal is required. The contact stabilization process would appear to be a promising alternative to conventional process configurations in such circumstances. A major question remaining is the propensity for nitrite accumulation, however. None of the previous research has addressed this question.

The purposes of the present research were as follow:

1. To determine the half-saturation and effective maximum specific growth rate coefficients for ammonia oxidizers and nitrite oxidizers growing on a high-nitrogen, synthetic wastewater.

2. To operate a bench-scale contact stabilization process to determine the effect of SRT and sludge recycle ratio on nitrification.

3. To evaluate a computer model that includes nitrite as a wastewater component by comparing it with experimental data.

CHAPTER 2
LITERATURE REVIEW

Microbiology

There are several species of microorganisms causing the oxidation of ammonia nitrogen to nitrite nitrogen. Principal organisms are the genera Nitrosomonas (N. europaea and N. monocella) and Nitrosococcus. Nitrosolobulus multiformis and Nitrosospira briensis isolated from soils are also known to carry out the oxidation of ammonia nitrogen to nitrite. Since Nitrosomonas, especially N. europaea, isolated from wastewater treatment environments has a major role, the generic term Nitrosomonas is used to refer to all ammonia-oxidation bacteria. These bacteria are chemoautotrophic bacteria which obtain energy through a chemical oxidation step and use inorganic carbon such as carbon dioxide, carbonic acid, bicarbonate, and carbonate as a carbon source.

The genera Nitrobacter (N. agilis and N. winogradsky) and Nitrosocystis are known as the nitrite-oxidizers in wastewater environments. Although Nitrosococcus mobilis and Nitrosospira gracilis have been isolated from marine environments, nitrite oxidizers are commonly referred to as Nitrobacter (Barnes & Bliss, 1983).

Stoichiometry

Ammonia oxidation has several steps making hydroxylamine and other unstable intermediates. The first step is the formation of hydroxylamine releasing little or no energy as in equation (2-1).

$$NH_4^+ + 0.5O_2 \longrightarrow NH_2OH + H^+ \qquad (2\text{-}1)$$

The subsequent step, oxidation of hydroxylamine to nitrite, is known as a semi-cyclic process involving the cytochrome system. A reaction has been summarized as in equation (2-2):

$$NH_2OH + O_2 \longrightarrow H^+ + NO_2^- + H_2O + \text{Energy} \qquad (2\text{-}2)$$

This step produces the majority of energy in the oxidation of ammonia. The complete equation for ammonia oxidation is equation (2-3).

$$NH_4^+ + 1.5O_2 \longrightarrow NO_2^- + H_2O + 2H^+ + (240 - 350\ \text{KJ}) \qquad (2\text{-}3)$$

There are no intermediate products in nitrite oxidation which is expressed in equation (2-4)

$$NO_2^- + 0.5O_2 \longrightarrow NO_3^- + (65 - 90\ \text{KJ}) \qquad (2\text{-}4)$$

If the components of Nitrosomonas and Nitrobacter are assumed to be represented as $C_2H_7NO_2$, the stoichiometric equation for cell growth is:

$$15CO_2 + 13NH_4^+ \longrightarrow 10NO_2^- + \underset{\underline{\text{Nitrosomonas}}}{3C_5H_7NO_2} + 23H^+ + 4H_2O \qquad (2\text{-}5)$$

$$5CO_2 + NH_4^+ + 10NO_2^- + 2H_2O \longrightarrow 10NO_3^- + \underset{\underline{\text{Nitrobacter}}}{C_5H_7NO_2} + H^+ \qquad (2\text{-}6)$$

Carbon dioxide is a carbon source for nitrifying bacteria and, also, has the buffering capacity against the change of proton concentration in water through changing chemical forms, e.g., carbon dioxide, bicarbonate and carbonate. The hydrogen ions produced in equations (2.1), (2,5) and (2,6) can combine with these carbon materials, therefore, three comprehensive equations can be made:

$$NH_4^+ + 1.5O_2 + 2HCO_3^- \longrightarrow$$
$$NO_2^- + 2H_2CO_3 + H_2O + (240\text{-}350\ KJ) \qquad (2\text{-}7)$$

$$13NH_4^+ + 23HCO_3^- \longrightarrow$$
$$8H_2CO_3 + 10NO_2^- + 3C_5H_7NO_2 + 19H_2O \qquad (2\text{-}8)$$

$$NH_4^+ + 10NO_2^- + 4H_2CO_3 + HCO_3^- \longrightarrow$$
$$10NO_3^- + 3H_2O + C_5H_7NO_2 \qquad (2\text{-}9)$$

Assuming the Nitrosomonas cell yield is 0.15 g VSS/(g NH_4^+ - N), equations (2-7) and (2-8) can be combined:

$$55NH_4^+ + 76O_2 + 109HCO_3^- \longrightarrow \underbrace{C_5H_7NO_2}_{\text{Nitrosomonas}} + 54NO_2^- + 57H_2O + 104H_2CO_3 \quad (2\text{-}10)$$

and assuming the Nitrobacter cell yield is 0.02 g VSS/(g NO_2 - N), equations (2-2) and (2-9) can be combined:

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \longrightarrow \underbrace{C_5H_7NO_2}_{\text{Nitrobacter}} + 3H_2O + 400NO_3^- \quad (2\text{-}11)$$

and the complete reaction for nitrification can be made by combining equations (2-10) and (2-11):

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \longrightarrow 0.021C_5H_7NO_2 + 1.041H_2O + 0.98NO_3^- + 1.88H_2CO_3 \quad (2\text{-}12)$$

The Maximum Specific Growth Rates and Half-Saturation Coefficients for Nitrosomonas and Nitrobacter

The coefficients such as maximum specific growth rates and half-saturation coefficients for Nitrosomonas and Nitrobacter, respectively, have important roles in a model for nitrification.

A pure *Nitrobacter* culture was studied to evaluate several kinetic parameters in nitrification (Gould and Lees, 1960). Williamson and McCarty (1975) proposed the infinite-dilution method to estimate half-saturation coefficients for *Nitrobacter* and *Nitrosomonas* using pure cultures of both microorganisms. The Lineweaver-Burk procedure was applied to estimate half-saturation coefficients in their study. A model for contact stabilization was adopted to estimate the maximum specific growth rate for *Nitrosomonas* (Gujer and Jenkins, 1975). The comparisons of experimental and simulation results gave the maximum specific growth rate of *Nitrosomonas* (Alexander et al., 1980). Eric and Murphy (1980) showed the different maximum specific growth rates for *Nitrobacter* and *Nitrosomonas* depending on different influent Total Kjeldahl Nitrogen (TKN) concentrations and used a first order differential equation to compare the evaluated values. 2-chloro-6-trichloromethyl pyridine (N-Serve) was used to inhibit *Nitrosomonas* activity when the specific growth rate of Nitrobacter was evaluated. Temperatures were not specified in their study. The infinite dilution method (Williamson and McCarty, 1975) was tested and compared with experimental results using a respirometer by Čech et al. (1985). They concluded that the infinite dilution method had more accuracy than their method in the estimate of the half-saturation coefficient for *Nitrosomonas*. Philbrook and Grady (1985) proposed the modified infinite-dilution method to estimate the half-saturation coefficient for the degradation of 2-chlorophenol. This method will be presented in Chapter 3 in this study.

Alleman (1984) presented maximum specific growth rates and half-saturation coefficients for Nitrosomonas and Nitrobacter. Terashiman and Ishikawa (1984) compared simulations and experimental results in an oxidation ditch and presented the half saturation coefficient for nitrification. Chudoba et al. (1985) investigated the nitrification kinetic parameters according to reactor types and found that the half-saturation coefficient and the maximum substrate utilization rate were higher in a plug flow (PF) reactor than in a completly mixed (CM) reactor. The average value for the half saturation coefficient for nitrification in a PF reactor was 0.65 g/m^3, as compared to 0.37 g/m^3 in a CM reactor. Henze et al. (1986) introduced several kinetic parameters in nitrification along with an activated sludge model. The maximum specific growth rate and the half saturation coefficient for ammonia oxidizers were 0.8 day^{-1} and 1.0 g NH_3-N/m^3 at 20°C and 0.3 day^{-1} and 1.0 g NH_3-N/m^3 at 10 °C, respectively. Antoniou (1989) investigated the maximum effective specific growth rate and the half saturation coefficient for nitrification in an activated sludge from Kanapaha water reclamation facility, Gainesville, FL. He found the maximum effective specific growth rate had a maximum value of 0.564 1/d at 20°C and average pH of 8.2. Half saturation coefficient was reported as 0.2 g NH_3-N/m^3 at a temperature of 20°C and a pH of 7.8. Gee (1990b) found the maximum specific growth rates and the half saturation coefficients for Nitrosomonas and Nitrobacter. Yoshioka et al. (1982 a, b) evaluated kinetic parameters of nitrifiers, e.g., Nitrosomonas and Nitrobacter, isolated from mud in a lake using direct counting method in a pure culture at 20°C temperature and pH 7.7±1.0. They determined the maximum specific growth rates and the half saturation coefficients for both microorganisms and found ammonia oxidizers in a mixed culture had the similar value of maximum specific growth rate as in a pure culture. Table 2-1 shows the summary of both kinetic parameters.

Kinetics and Models in Nitrification

The nitrification could be divided into two steps: ammonia oxidation and nitrite oxidation. Equation (2-13) shows each reaction step.

$$NH_4^+ \xrightarrow{r_{NH4}} NO_2^- \xrightarrow{r_{NO2}} NO_3^- \qquad (2\text{-}13)$$

r_{NH4} and r_{NO2} represent the oxidation rate of ammonia and nitrite nitrogen, respectively. Though two reaction rates, r_{NH4} and r_{NO2}, are considered as a zero order (Wong-Chong et al., 1975), the Monod type model has been widely accepted to express each reaction (Sharma & Ahlert, 1977). The expression of a Monod equation for the growth of Nitrosomonas:

$$r_s = \frac{\mu_m}{Y_{NH4A}} = \frac{\hat{\mu}_{ANH4}}{Y_{NH4A}} \frac{S_{NH4}}{K_{NH4A} + S_{NH4}} \qquad (2\text{-}14)$$

where, r_s = ammonia oxidation rate, g/m^3 day

μ_m = specific growth rate of Nitrosomonas, day^{-1}

$\hat{\mu}_{ANH4}$ = maximum specific growth rate for Nitrosomonas, day^{-1}

S_{NH4} = concentration of ammonia nitrogen, g/m^3

Y_{NH4A} = yield coefficient for ammonia oxidizing bacteria, g/m^3

K_{NH4A} = half-saturation coefficient for ammonia oxidizing bacteria, g/m^3

Equation (2-14) can be used to express the rate of nitrite oxidation in terms of Nitrobacter with nitrite as a substrate. $\hat{\mu}_{ANH4}$, S_{NH4}, K_{NH4A} and Y_{NH4A} will be replaced with $\hat{\mu}_{ANO2}$, S_{NO2}, K_{NO2A} and Y_{NO2A}, respectively, when nitrite oxidation is considered.

Since dissolved oxygen is frequently present at a level low enough to limit ammonia oxidation, the growth rate equation should consider the effect of dissolved oxygen. The rate equation for ammonia oxidation including the effects of ammonia nitrogen and, also, dissolved oxygen is:

$$r_s = \frac{\mu_m}{Y_{NH4A}} = \frac{\hat{\mu}_{ANH4}}{Y_{NH4A}} \frac{S_{NH4}}{K_{NH4A} + S_{NH4}} \frac{S_O}{K_{ONH4} + S_O} \qquad (2\text{-}15)$$

Table 2-1. Characteristic parameters for nitrifying bacteria.

Process	μ_{ANH4}[1] (day^{-1})	K_{NH4A}[2] (mg NH_4-N/L)	Environment	References
Nitrification		0.5(20°C)	P/C[3]	(Willamson,1978)
(Biomass:	0.65(21°C)		A/S[4]	(Gujer, 1975)
Nitrosomonas)	0.34(12°C)		A/S	(Gujer, 1975)
	0.65(20°C)		A/S	(Dold, 1980)
	0.40(20°C)	2.0(20°C)	A/S	(Stall, 1974)
	0.33(20°C)	1.0(20°C)	A/S	(Downing, 1964)
	1.08(20°C)	0.063(20°C)	A/S	(Poduska, 1975)
	1.50(30°C)		P/C	(Engel, 1958)
	0.55(20°C)		A/S	(Alexander, 1980)
	0.45(20°C)		A/S	(Beccari, 1979)
	0.96-1.92	0.6-3.6	A/S	(Alleman, 1984)
	0.6(20°C)		A/S	(Warner, 1986)
	0.8(20°C)	1.0(20°C)	A/S	(Henze,1986)
	0.3(10°C)	1.0(10°C)	A/S	(Henze, 1986)
	0.28(15°C)	0.2(20°C)	A/S	(Antoniou, 1989)
	0.56(20°C)		A/S	(Antoniou, 1989)
	0.576(23°C)	0.7(23°C)	P/C	(Gee, 1990)
	0.58(20°C)	2.8(20°C)	A/S	(Yoshioka,1982)
		0.7 (PF[5])	A/S	(Chudoba, 1985)
		0.37 (CM[6])	A/S	(Chudoba, 1985)
		2.59-4.59(20°C)	SRW[7]	(Stratton, 1967)
	0.65(20°C)	0.6(20°C)	TSW[8]	(Knoles, 1965)

---

[1] maximum specific growth rate for Nitrosomonas

[2] half-saturation coefficient for Nitrosomonas

[3] pure culture

[4] activated sludge

[5] plug flow reactor

[6] completed mixed reactor

[7] synthetic river water

[8] Thames estuary water

Table 2-1. continued

Process	μ_{ANO2}[9] (day^{-1})	K_{NO2A}[10] (mg NO_2-N/L)	Environment	References
Nitratification (Biomass: *Nitrobacter*)	0.14(20°C)		A/S	(Downing, 1964)
		0.07(20°C)	P/C	(Willamson, 1978)
	1.44(20°C)		A/S	(Poduska, 1975)
	1.39(30°C)	22.0(20°C)	P/C	(Boon, 1962)
		(0.34-1.77(20°C)	SRW	(Stratton, 1967)
	0.84(20°)	1.9(20°C)	TEW	(Knoles, 1965)
	1.99(28°C)	5.01(28°)	P/C	(Gould,1960)
	0.27(20°C)		A/S	(Beccari, 1979)
	0.48-1.44	0.3-1.7	A/S	(Alleman, 1984)
	0.14(20°C)		A/S	(Downing, 1964)
		0.07(20°C)	P/C	(Willamson,1978)
	1.44(20°C)		A/S	(Poduska, 1975)
	0.42(23°C)	1.02(23°C)	P/C	(Gee, 1990 b)
	0.81(20°C)	0.14(20°C)	A/S	(Yoshioka, 1982)
	1.39(30°C)	22.0(20°C)	P/C	(Boon, 1962)
		(0.34-1.77,20°C)	SRW	(Stratton, 1967)
	0.84(20°)	1.9(20°C)	TEW	(Knoles, 1965)
	1.99(28°C)	5.01(28°)	P/C	(Gould,1960)
	0.27(20°C)		A/S	(Beccari, 1979)
	0.48-1.44	0.3-1.7	A/S	(Alleman, 1984)
	0.42(23°C)	1.02(23°C)	P/C	(Gee, 1990 b)
	0.81(20°C)	0.14(20°C)	A/S	(Yoshioka,1982)

---

[9] maximum specific growth rate for *Nitrobacter*

[10] half-saturation coefficient for *Nitrobacter*

Where, S_0 = concentration of dissolved oxygen, g/m^3

K_{ONH4} = oxygen half-saturation coefficient for Nitrosomonas, g/m^3

When nitrite oxidation is considered, K_{ONO2} will replace K_{ONH4} and S_{NO2} will replace S_{NH4}. In order to use these kinetic equations to simulate both reactions, i.e., ammonia and nitrite oxidations, coefficients in equation (2-15) should be estimated.

Based on equation (2-15), the model for nitrification was developed (Ekama and Marais, 1978; Haandel et al., 1982; Henze, 1986; Lijklema, 1973; Water Research Commission, 1984; Gee et al., 1990). Lijklema (1973) developed a model simulating the growth of heterotrophic bacteria, the growth of a predator and nitrification. His work showed an agreement between results of experiments and simulations. The Marais-Ekama activated sludge model (Ekama and Marais, 1978) was verified by Nichollas (1982) and showed a good agreement except the values of TKN and MLSS concentrations in an aeration tank. The discrepancy was explained as being due to the difficulty in the estimating nonbiodegradable particulate COD matters. Warner et al. (1986) carried out experiments for the digestion of wasting activated sludge using an anoxic-aerobic system and compared the simulations data from the model proposed by Alexander et al. (1988). Henze et al. (1986) developed a model combining carbon oxidation, nitrification and denitrification. Thirteen components in wastewater and 8 reactions were incorporated. The characterization methods for the constituents in wastewater and the procedures for estimating parameters in the model were presented in their work. Bidstrup and Grady (1988) wrote a computer program for a model proposed by Henze et al. (1986).

Nitrite Build-up in Nitrification

When the rate of ammonia oxidation is greater than that of nitrite oxidation ($r_{NH4} > r_{NO2}$ in Equation (2-13)), nitrite starts accumulating in an oxidation tank. Warington, cited in Anthonisen et al. (1976), observed nitrite in 1876, before the identification of nitrifying organisms. When a soil column was used to oxidize a higher concentration of ammonia nitrogen, e.g., 5000 mg NH_4^+-N/L, nitrite was accumulated (Stojanovic and Alexander, 1957). Free Ammonia (FA) and Free Nitrous Acids (FNA) inhibited Nitrobacter activity and caused the nitrite build-up (Butt and Lees, 1960; Prakasam and Loehr, 1972; Wong-Chong and Loehr, 1975; Anthonisen et al., 1976; Anthonisen et al., 1977; Verstrate et al., 1977; Wong-Chong and Loehr, 1978; Chudoba et al., 1985). Anthonisen et al. (1977) made several diagrams showing inhibitory concentrations of FA and FNA on ammonia and nitrite oxidations at different pH. Verstrate et al. (1977) found lower concentrations of FA

(0.29 - 0.3 g FA/m^3) caused the inhibition to the oxidation of ammonia than those (0.1 - 1 gFA/m^3) reported by Anthonisen et al. (1977). Fort et al. (1980) investigated the inhibitory effects of FA and FNA on nitrification and developed a couple of equations showing concentrations of FA and FNA as a function of temperature and pH. Their experiment showed that the inhibitory effects on nitrification occurred at the same range of the FA and FNA concentrations reported by Anthonisen et al. (1977). Alleman (1984) investigated the nitrite build-up in nitrification at Sequence Batch Reactors (SBR) and found FA was a predominant inhibitor under several conditions, e.g., a reduced temperature, limiting oxygen and carbon dioxide supply, elevated pH and excess solids wasting. Nitrite accumulated at a concentration of FA as low as 0.05 gFA/m^3. Randall et al. (1984) studied the effects of temperature on nitrite build-up. They found nitrite accumulated when the temperature was lower than 16°C. They concluded the temperature impact is higher on Nitrobacter than on Nitrosomonas; therefore, nitrite can accumulate under low temperature conditions. Turk and Mavinic (1986) tried to accumulate nitrite in a series of aeration tanks with high nitrogen influent and found initially accumulated nitrite was oxidized after all despite a same FA concentration was maintained in aeration tanks. They attributed this phenomenon to the acclimation of biomass to high concentrations in influent.

Nitrification in Contact Stabilization System

Contact stabilization was used to treat domestic wastewater based on empirical observations (Uillrich and Smith, cited in Gujer and Jenkins (1975)). Gujer and Jenkins (1975) adopted a term "Nitrification efficiency" - the ratio of nitrate in contact tank to that in reaeration tank- to explain the partial nitrification in contact stabilization process. They assumed the nitrate in reaeration tank represented the total amount of oxidized nitrogen by autotrophic biomass. They made a graph illustrating the nitrification efficiency with respect to recycle ratio. According to this graph, the nitrification efficiency increases exponentially when sludge recycle ratio is lower than 100%, whereas the efficiency reaches the plateau when sludge recycle ratio is higher than 200%. however, their experiments did not display the effect of recycle ratio on nitrification efficiency since the recycle ratios in process operation were near or above 100%. And experimental data did not demonstrate the effect of temperatures on nitrification efficiency within reactor operation temperatures, 12°C and 20°C. The change of contact fractional mass did not show the effects on nitrification efficiency. Alexander et al. (1980) operated a laboratory scale contact stabilization process and evaluated an activated sludge model proposed by Dold et al., cited in Alexander et al. (1980). The performance of a contact stabilization process was recorded at two different SRTs under a constant temperature, 20°C, and a constant recycle ratio, 200%. At 6 days of SRT, nitrification efficiency was 75%, whereas 75.8% at 10 days of SRT.

CHAPTER 3

DETERMINATION OF AMMONIA AND NITRITE HALF-SATURATION COEFFICIENTS FOR NITRIFICATION

Introduction

An infinite dilution method was employed for the estimation of substrate half-saturation coefficients for ammonia (K_{NH4A}) and nitrite oxidizers (K_{NO2A}). Williamson and McCarty (1975) first used this method to measure the coefficient by employing the Lineweaver-Burk equation to analyze their data. However, because their technique of analysis required three or more trials to provide a reliable estimate of the half-saturation coefficient, the modified infinite dilution procedure was used instead. Philbrook and Grady (1985) used the modified infinite dilution procedure to determine the half-saturation coefficient for the degradation of 2-chlorophenol from the results of two consecutive experiments.

Development of an Expression for Measurement of K_{NH4A} and K_{NO2A} Using Fed-Batch Cultures

When a microbial culture is placed in a batch reactor and substrate is added continually at a rate less than the maximum substrate utilization rate at which the culture can use it, the culture will regulate the substrate concentration to a value consistent with the rate of addition. If the volume of feed added is small with respect to the reactor volume and if the biomass formed over the duration of the experiment is small with respect to the mass carrying out the removal, then a pseudo-steady-state will be reached during which the substrate concentration in the reactor is constant.

From Monod kinetics,

$$U_A \; X_{B,A} = \hat{U}_A \; X_{B,A} \frac{S_N}{K_{NH} + S_N} \tag{3-1}$$

where U_A = specific substrate removal rate
= μ_{ANH4} / Y_{ANH4} for nitritification, g NH_4^{+1}-N/(g Nitrosomonas d)
= μ_{ANO2} / Y_{ANO2} for nitratification, g NO_2^{-1}-N/(g Nitrobacter d)

Y_{ANH4} = yield coefficient for Nitrosomonas, g cells formed per g NH_4^{+1}-N oxidized

Y_{ANO2} = yield coefficient for Nitrobacter, g cells formed per g NO_2^{-1}-N oxidized

$\hat{U}_A$ = maximum specific substrate utilization rate of either nitritification or nitratification

$X_{B,A}$ = nitrogen oxidizing bacteria, g cells/m3
= X_{BANH4} for Nitrosomonas
= X_{BANO2} for Nitrobacter

S_N= concentration of nitrogen components, g N/m^3
= S_{NH}, ammonia nitrogen for nitritification, g NH_4^{+1}-N/m^3
= S_{NO2}, nitrite nitrogen for nitratification, g NO_2^{-1}-N/m^3

K_{NH}= half-saturation coefficients, g substrate/m^3
= K_{NH4A} for Nitrosomonas, g NH_4^{+1}-N/m^3
= K_{NO2A} for Nitrobacter, g NO_2^{-1}-N/m^3

Equation (3-1) can be rearranged as follows:

$$K_{NH} = \left(\frac{\hat{U}_A \ X_{B,A}}{U_A \ X_{B,A}} - 1 \right) S_N \qquad (3\text{-}2)$$

the substrate concentration, S_N, can be measured by sampling from the reactor. Expressions for $U_A \ X_{B,A}$ and $\hat{U}_A \ X_{B,A}$ can be developed from a mass balance on a fed batch reactor (see Figure 3-1 for a schematic of a fed batch reactor):

$$Q \ S_{NO} - U_A X_{B,A} \ V = \frac{d(V \ S_N)}{dt} \qquad (3\text{-}3)$$

Where Q = feed flow rate, m^3/h
S_{NO} = feed substrate concentration, g/m^3
V = bioreactor volume, m^3

When reactor volume, V, is large relative to the feed rate, equation (3-3) may be expressed as:

$$Q \ S_{NO} - U_A \ X_{B,A} \ V = V \frac{dS_N}{dt} \qquad (3\text{-}4)$$

or

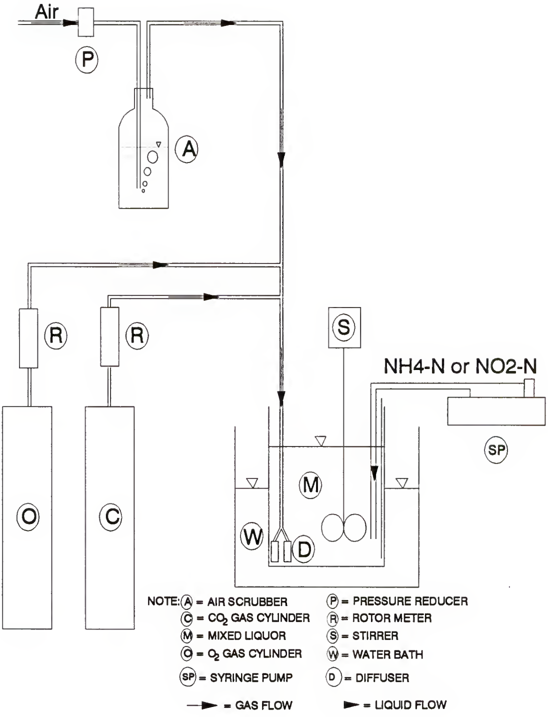


Figure 3-1. A schematic of a fed-batch reactor.

$$\frac{Q\ S_{No}}{V} = \frac{dS_N}{dt} + U_A\ X_{B,A} \qquad (3\text{-}5)$$

If S_N >> K_{NH} and the substrate application rate ($Q_1\ S_{NO}/V$) exceeds the culture's utilization capacity, then U_A is equal to $\hat{U}_A$. Rearranging equation (3-5):

$$\hat{U}_A\ X_{B,A} = \frac{Q_1\ S_{No}}{V} - \frac{dS_N}{dt} \qquad (3\text{-}6)$$

If the substrate addition rate is less than the culture's utilization capacity, a pseudo-steady-state will eventually be attained. In this case, $dS_N/dt = 0$, and

$$U_A\ X_{B,A} = \frac{Q_2\ S_{No}}{V} \qquad (3\text{-}7)$$

On the basis of these equations, it is possible to determine the K_{NH} for nitrifying cultures by carrying out two experiments. In the first experiment (phase A), substrate is applied at a rate in excess of the culture's maximum oxidizing rate. By measuring S_N periodically, the term dS_N/dt can be found and used to calculate $\hat{U}_A\ X_{B,A}$ from equation (3-6). In a subsequent experiment (phase B), substrate is applied at the appropriate rate so that $Q_2\ S_{NO}/V$ is approximately equal to one-half $\hat{U}_A\ X_{B,A}$. The resulting steady-state value of S_N, together with the corresponding U_A $X_{B,A}$ calculated from equation (3-7) is used to calculate K_{NH} from equation (3-2).

Materials and Methods

Summary of Experiments

The half-saturation coefficients for ammonia and nitrite oxidization were determined by the use of laboratory scale fed-batch experiments. Two 2-L glass beakers, two stirring motors, two syringe pumps were used for this experiment. A total of 5 experiments were carried out for each oxidation step, i.e., nitritification and nitratification.

Microorganisms

The microorganisms of the wasting sludge from a bench-scale contact stabilization system were used in this experiment. In order to maintain same SRT in contact stabilization process, a certain amount of sludge was withdrawn from reaeration tank through a masterflex pump and stored in a refrigerator to keep down the activity of microorganisms. This refrigerated sludge was were aerated to restore the activity of microorganisms in sludge.

Experimental Procedures

This experiment consists of two phases:

i) Phase A was to estimate the unit oxidization rate with excess ammonia or nitrite nitrogen.

ii) Phase B was to find the pseudo-steady-state concentration of either ammonia or nitrite nitrogen at a selected nitrification.

The value of $\hat{U}_A\ X_{B,A}$ in Equation (3-6) can be estimated based on the substrate feeding, $(Q\ S_N)/V$, and accumulation rate, dS_N/dt, in Phase A experiment. $U_A\ X_{B,A}$ and steady-state value of S_N can be also evaluated in Phase B experiment.

800 mL of the refrigerated wasting sludge from the contact stabilization system was aerated for at least one hour to acclimate to a room temperature, 25±1°C, before inoculating two 2L glass beakers. In order to make an approximate concentration of 270 mg/L of Mixed Liquor Suspended Solids (MLSS) in each reactor, 1300 mL of the effluent from a secondary clarifier at the University of Florida Sewage Treatment Plant (UFSTP) was added to each beaker with 400 mL of acclimated wasting sludge. Micronutrient for the growth of microorganisms such as 1.7 mL of 28.7 g NaH_2PO_4/L , 1.7 mL of 0.06 g $FeCl_3 \cdot 6H_2O$/L, and 1.7 mL of 22.5 g $MgSO_4 \cdot 7H_2O$/L were added. In order to neutralize the acid produced from nitrification, 5 g of sodium bicarbonate were provided to each reactor.

The indoor air through a pressure reducer (Dayton Electric, Buffalo Grove, IL) was used to provide the air to both reactors. The debris in indoor air was removed through a cotton filter and an air scrubber was used to humidify indoor gas, respectively. A pressurized carbon dioxide gas was used to maintain a pH of 7 and the pure oxygen was introduced to ensure the Dissolved Oxygen (DO) concentration was always above 12 g O_2/m^3 during experiment. These gases were connected to indoor air tubes through Y connectors. Two stone-to-air diffusers were placed at the bottom of each reactor with a Y-connector as in Figure 3-1. In order to maintain a temperature of 25±1 °C, a water bath (Blue Island, IL) was used. Mixing was provided using a plastic Nalgene propeller attached to a stirring motor.

In order to achieve the same mixing intensity of the contact tank in contact stabilization system in each batch reactor, the stirring rate of the mixer in each batch reactor was adjusted using the following relationship (American Water Works Association Research Foundation, 1991):

$$\frac{N_C^{3/2}}{V_C^{1/2}} = \frac{N_B^{3/2}}{V_B^{1/2}} \qquad (3-8)$$

where, N_C = revolution rate of the mixer in contact tank, rpm

N_B = revolution rate of the mixer in each batch reactor, rpm

V_C = volume of contact tank, L

V_B = volume of each batch reactor, L

From equation (3-8), N_B is

$$N_B = \left| \frac{V_B^{1/2}}{V_C^{1/2}} N_C^{3/2} \right|^{2/3} \qquad (3-9)$$

N_B is to be 685 rpm since V_B, V_C and N_C are 1.7 L, 2.5 L and 780 rpm, respectively. This revolution rate was maintained in both batch reactors during experiment. Digital Optical Tachometer (Model-IV, Monarch Instrument, Amherst, NH) was used to measure the rpm of the mixer in each tank.

In the experiment of the half-saturation coefficient for Nitrosomonas, a 5000 g NH_4^{+1}-N/m^3 ammonium chloride solution was fed into the Phase A reactor by a syringe pump (model 355, Orion, Boston, MA) through a length of Tygon tube (0.78 mm I.D.) which reached to the bottom of a reactor. The feed rate to phase A reactor was 3.47 mL/hr to make a rate in excess of the culture's maximum nitrification rate. This rate was selected by trial and error. Initially, 5 mL of the above solution was spiked to make a 15.0 g NH_4^{+1}-N/m^3 in the Phase A reactor.

In the Phase B experiment, the procedure of Phase A experiment was used except for the feed rate of a ammonium chloride solution and the initial spike. The feed rate, 0.68 mL/hr, was selected to make a pseudo-steady-state condition by trial and error. The reactor was spiked to make 5 g NH_4^{+1}-N/m^3 by 1.7 mL of a 5000 g NH_4^{+1}-N/m^3 ammonium chloride solution.

In experiments for the half-saturation coefficient for Nitrobacter, a 5000 g NO_2^{-1}-N/m^3 sodium nitrite solution was fed into the phase A reactor. Since a high concentration of nitrite, i.e., 30 g NO_2^{-1}-N/m^3 showed the substrate inhibition to Nitrobacter as in Figure 3-2, no nitrite was added to phase A reactor for initial 2 hours experimental time. A feeding concentration in Figure 3-2 represents the estimated NO_2^--N concentration based on feeding rate without oxidization reaction. During this period, microorganisms were accumulated to nitrite. 2 mL of a 5000 g NO_2^{-1}-N/m^3 sodium nitrite solution initially was spiked to make 6 g NO_2-N/m^3 in each reactor. In Figure 3-2, a feeding concentration refers the estimated concentration of nitrite nitrogen based upon the sodium nitrite feeding rate.

In the phase B experiment, a feed rate of 0.63 mL/hr of 5000 g NO_2^{-1}-N/m^3 sodium nitrite solution was chosen to make a pseudo-steady-state by trial and error. 1 mL of 5000 g NO_2^{-1}-N/m^3 sodium nitrite solution was initially spiked to bring the concentration to 3 g NO_2^{-1}-N/m^3 in the phase B reactor.

Analytical Methods

Ammonia Nitrogen. Ammonia nitrogen was analyzed using a gas sensing combination electrode (Orion model 9512, Boston, MA) with a Digital Ionanalyzer (Orion model 701A, boston, MA) according to 417 E in the Standard Methods (APHA, et al., 1985). 30 mL of samples from each reactor taken by a syringe was filtered through a pore size 0.45 μm membrane filter (Gelman GN-6, Ann Arbor, MI) after prefiltration with a pore size 1.6 μm glass microfibre filter (Whatman GF/C, Maid stone, England).

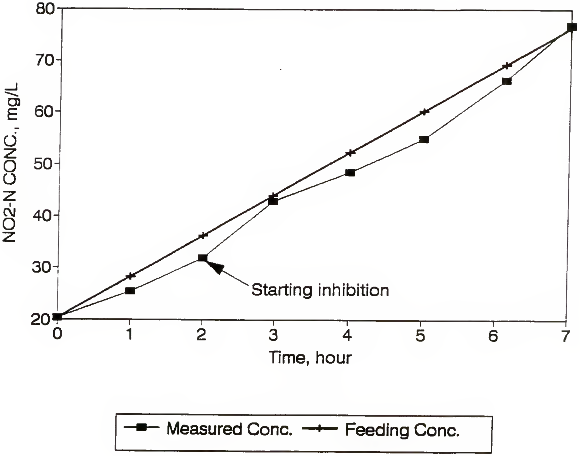


Figure 3-2. Nitrite nitrogen inhibition to Nitrobacter.

5 ml of filtered samples were used to analyze the concentrations of ammonia nitrogen. In order to minimize the ammonia volatilization, a 17 ml glass vial having a very narrow neck and therefore a very small surface exposed to the air were used. The mixing was provided by a magnetic stirrer (Model PC353, Corning, Corning, NY) with a micro bar (Ø1/8" x L1/2") before adding 0.3 ml of a 5M NaOH solution. This NaOH solution contained 0.05M Disodium Ethylene Diamine Tetra Acetic Acid (EDTA), 10% (V/V) methanol and 5M NaOH. After a stable reading was displayed, the mV value was recorded. After calibration against standard solutions, the concentrations of ammonia nitrogen in samples were determined.

Mixed Liquor Suspended Solids (MLSS). Samples of 5 mL from each reactor and 100 mL from an effluent tank were taken to measure the concentrations of Mixed Liquor Suspended Solids (MLSS). These samples were filtered through a predried and preweighted a 1.2 μm glass microfibre filter (Whatman GF/C, Maidstone, England). After drying in an oven at a temperature of 103°C for at least three hours, the MLSS were estimated by the difference of filtration paper weight.

Nitrite and Nitrate Nitrogens. Two oxidized nitrogen forms, nitrite and nitrate nitrogen were measured using an Ion Chromatography (Dionex model 2000i, Sunnyvale, CA).

The extra filtered samples, approximately 5 mL, after an ammonia nitrogen analysis were used to inject into this instrument. Since a sample had high concentrations of nitrate nitrogen, samples were diluted to a factor of 20 times. A standard solution having 11.288 mg NO_2^--N/L and 15.215 mg NO_3^--N/L was used to calibrate.

Results of Experiments

Experimental results of the half-saturation coefficients for ammonia and nitrite oxidizers are shown in Tables 3-1 and 3-2, respectively. In these Tables, A and B refers Phase A and B experiments, respectively. Phase A was used to obtain $\hat{U}_A X_{B,A}$ and $U_A X_{B,A}$ and a steady-state value were estimated at Phase B. The half-saturation coefficient for Nitrosomonas ranged from 0.728 g NH_4^{+1}-N/m^3 to 0.455 g NH_4^{+1}-N/m^3 with an average of 0.58 g NH_4^{+1}-N/m^3 at a temperature of 25°C and an average pH of 7. The duration time for this experiment was 7 hours. The results of 5 pairs of experiments are shown in Figures 3-3, 3-4 and 3-5.

The values for the half-saturation coefficient for Nitrobacter ranged from 0.883 g NO_2^{-1}-N/m^3 to 0.516 g NO_2^{-1}-N with an average of 0.719 g NO_2^{-1}-N/m^3 under same conditions of the experiment for Nitrosomonas. The results of 5 pairs of experiments are shown in Figures 3-6, 3-7 and 3-8.

Table 3-1. Summary of K_{NH4A} calculation for the experimental data.

Exp #	MLSS g/m^3	Avg. pH	S_{NH40} g/m^3	F mL/hr	$F S_{NH40}/V$ g/m^3 hr	dS_{NH4}/dT g/m^3 hr	0 X g/m^3 hr	UX g/m^3 hr	0X/UX	S_{NH4} g/m^3	K_{NH4A} g/m^3
7/9 A	252.6	7	5000	3.47	10.206	5.169	5.037		1.685		0.685
7/9 B	242.0	7	5000	1.016	2.988			2.988		1	
7/11 A	321.1	7	5000	3.47	10.206	4.428	5.778		1.934		0.728
7/11 B	326.3	7	5000	1.016	2.988			2.988		0.72	
7/12 A	247.4	7	5000	3.47	10.327	4.957	5.370		1.776		0.543
7/12 B	257.9	7	5000	1.016	3.024			3.204		0.70	
7/17 A	273.7	7	5000	3.47	10.206	5.328	4.878		1.632		0.455
7/17 B	273.7	7	5000	1.016	2.988			2.988		0.72	
7/18 A	268.4	7	5000	3.47	10.206	4.781	5.425		1.815		0.455
7/18 B	263.2	7	5000	1.016	2.988			2.988		0.60	

Average Value of $K_{NH4A} = 0.58\ g/m^3$
Standard Deviation $= 0.107\ g/m^3$

Table 3-2. Summary of K_{NO2A} calculation for the experimental data.

Exp \#	MLSS g/m³	Avg. pH	S_{NO20} g/m³	F mL/hr	$F S_{NO20}/V$ g/m³ hr	dS_{NO2}/dT g/m³ hr	0X g/m³ hr	UX g/m³ hr	0X/UX	S_{NO2} g/m³	K_{NO2A} g/m³
10/25 A	130	7	5000	1.36	3.968	1.309	2.677		1.441		0.883
10/25 B	130	7	5000	0.68	1.857			1.857		1.99	
10/28 A	135	7	5000	1.36	4.000	0.933	3.067		1.534		0.800
10/28 B	135	7	5000	0.68	2.000			2.000		1.499	
10/31 A	130	7	5000	1.36	4.000	0.787	3.213		1.607		0.607
10/31 B	125	7	5000	0.68	2.000			2.000		1.00	
11/1 A	120	7	5000	1.36	4.000	0.969	3.031		1.516		0.516
11/1 B	125	7	5000	0.68	2.000			2.000		1.00	
11/8 A	125	7	5000	1.36	4.000	0.688	3.312		1.656		0.787
11/8 B	130	7	5000	0.68	2.000			2.000		1.2	

Average Value of K_{NO2A} = 0.72 g/m³
Standard Deviation = 0.14 g/m³

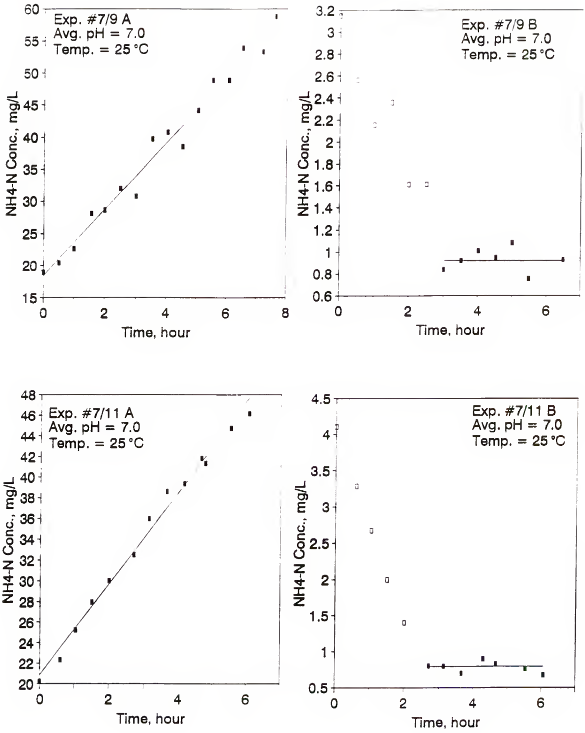


Figure 3-3. Determination of K_{NH4A} using fed batch experiments 7/9 A, 7/9 B, 7/11 A and 7/11 B (■: Data used for estimation).

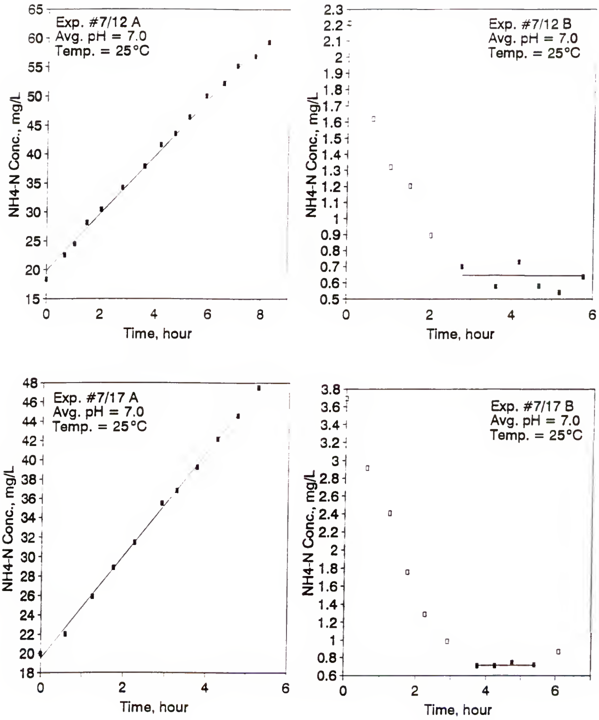
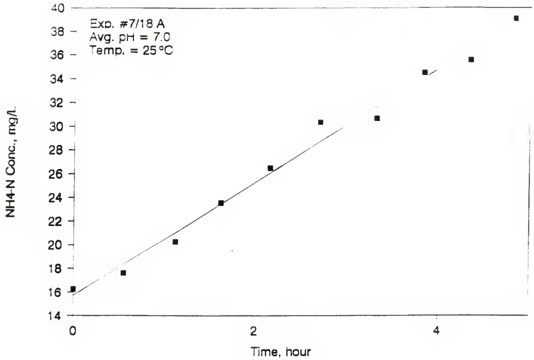


Figure 3-4. Determination of K_{NH4A} using fed batch experiments 7/12 A, 7/12 B, 7/17 A and 7/17 B (■: Data used for estimation).



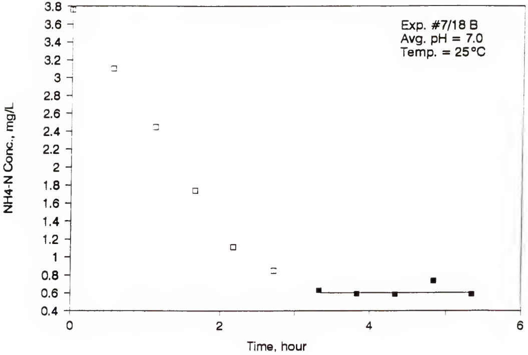


Figure 3-5. Determination of K_{NH4A} using fed batch experiments 7/18 A and 7/18 B (■: Data used for estimation).

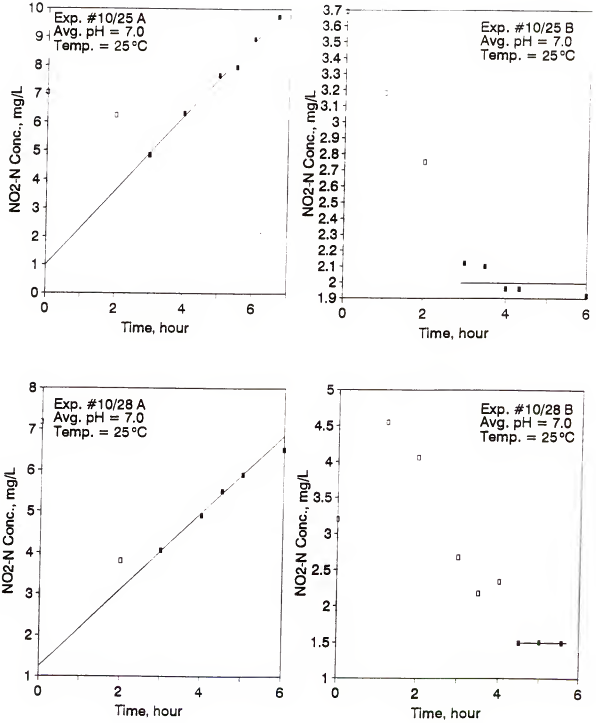


Figure 3-6. Determination of K_{NO2A} using fed batch experiments 10/25 A, 10/25 B, 10/28 A and 10/28 B (■: Data used for estimation).

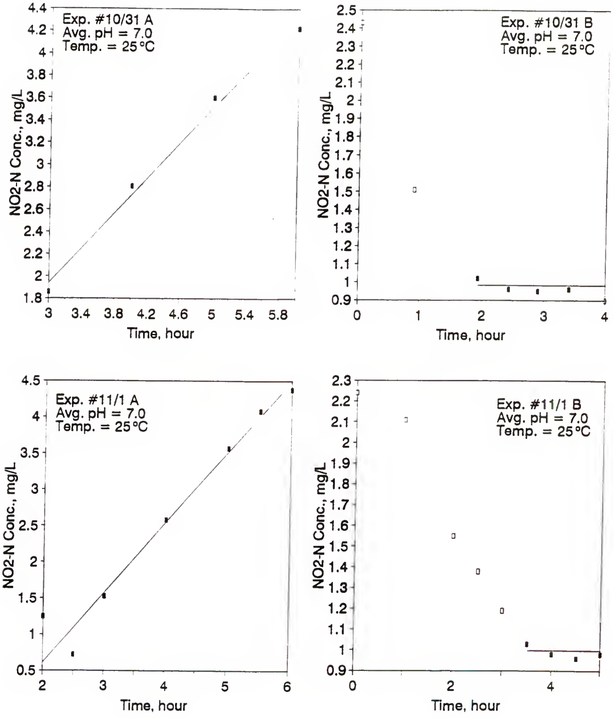
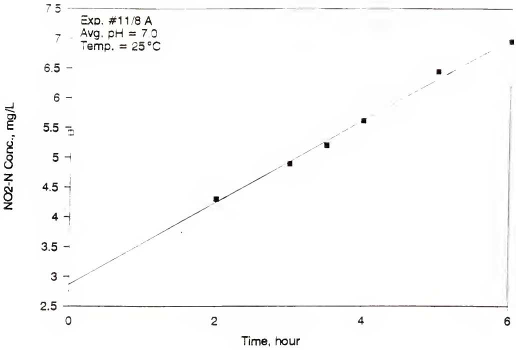


Figure 3-7. Determination of K_{NO2A} using fed batch experiments 10/31 A, 10/31 B, 11/1 A and 11/1 B (■: Data used for estimation).



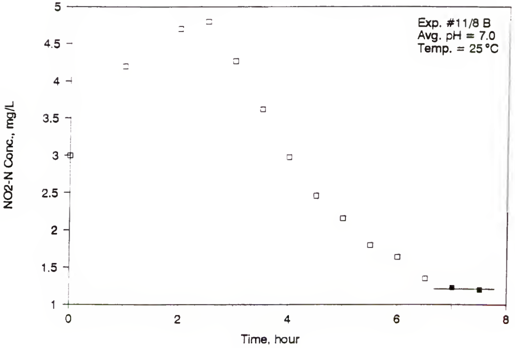


Figure 3-8. Determination of K_{NO2A} using fed batch experiments 11/8 A and 11/8 B (■: Data used for estimation).

CHAPTER 4

DETERMINATION OF THE EFFECTIVE MAXIMUM SPECIFIC GROWTH RATES OF NITROGEN OXIDIZING BACTERIA[1]

Introduction

The maximum specific growth rates of the nitrogen oxidizing bacteria in activated sludge are most crucial parameters describing the growth of the autotrophic bacteria. Two maximum specific growth rates are $\hat{\mu}_{ANH4}$ and $\hat{\mu}_{ANO2}$ for ammonia oxidizing and nitrite oxidizing bacteria, respectively. In this chapter, $\hat{\mu}_A$ refers to either microorganism's maximum specific growth rates. The correct estimation of $\hat{\mu}_A$ will determine the nitrification capacities in a wastewater treatment plant, the possibility of nitrite build-up in an aeration tank and the minimum Sludge Retention Time (SRT), below which washout of the nitrogen oxidizers would occur.

Since the $\hat{\mu}_A$ has a big effect on nitrification, the estimation of these parameters is very important for simulating nitrification using a computer model.

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[1] Nitrogen oxidizing bacteria include ammonia and nitrite oxidizing bacteria

Basis for the Determination of $\mu_A - b_A$ Using a Batch Culture

When nitrogen oxidizing bacteria are grown in a batch reactor at non-limiting nitrogen and dissolved oxygen concentrations, their concentrations vary according to the following equation:

$$\frac{dX_{B,A}}{dt} = (\mu_A - b_A)\ X_{B,A} \tag{4-1}$$

where, $X_{B,A}$ = active autotrophic biomass, g/m^3

= X_{BANH4} in ammonia oxidization

= X_{BANO2} in nitrite oxidization

b_A = autotrophic decay coefficient in either ammonia or nitrite bacteria

$\frac{dX_{B,A}}{dt}$ = growth rate of autotrophic biomass, g/m^3

If the production of nitrite is completely growth associated and nitrite were not further oxidized to nitrate in the case of ammonia nitrogen, we would have:

$$\frac{d[NO_2^{-1}-N]}{dt} = \frac{1}{Y_{ANH4}}\ \mu_{ANH4}\ X_{BANH4} \tag{4-2}$$

where, $\frac{d[NO_2^{-1}-N]}{dt}$ = accumulation rate of nitrite, g/m^3 day

Y_{ANH4} = growth yield for ammonia oxidizers, g/g

Equation (4-1) can be integrated subject to the initial condition $X_{BANH4}(0) = X_{BANH4o}$ to give:

$$X_{BANH4}\ (t) = X_{BANH4o}\ e^{(\mu_{ANH4} - b_A)\ t} \tag{4-3}$$

combining equations (4-2) and (4-3), the following expression is obtained:

$$\frac{d[NO_2^{-1}\text{-}N]}{dt} = \frac{1}{Y_{ANH4}}\ \mu_{ANH4}\ X_{BANH4o}\ e^{(\mu_{ANH4} - b_A)\ t} \tag{4-4}$$

which upon integration yields:

$$[NO_2^{-1}\ \text{-}N]_t = \frac{\mu_{ANH4}\ X_{BANH4o}\ e^{(\mu_{ANH4} - b_A)\ t}}{Y_{ANH4}\ (\mu_{ANH4} - b_A)} + [NO_2^{-1}\text{-}N]_o - \frac{\mu_{ANH4}\ X_{BANH4o}}{Y_{ANH4}(\mu_{ANH4} - b_A)} \tag{4-5}$$

where $[NO_2^{-1}\text{-}N]_o$ is the initial nitrite nitrogen concentration. With the exception of an initial start-up time, the sum of the second and third terms in the right hand side of equation (4-5) will be negligible since they are constants while the first term increases exponentially.

If the natural logarithm is taken in both sides without the second and third terms in equation (4-5), the following equation can be derived:

$$\ln\ [NO_2^{-1}\text{-}N]_t = \ln \frac{\mu_{ANH4}\ X_{BANH4o}}{Y_{ANH4}(\mu_{ANH4} - b_A)} + (\mu_{ANH4}\text{-}b_A)*t \tag{4-6}$$

In the mixed culture experiments carried out, most of nitrite produced was further oxidized to nitrate by nitrifying bacteria. The sum of the nitrite and nitrate nitrogen concentrations thus gives the total amount of nitrite that would be present in the absence of the nitrite oxidizers. Assimilation of nitrite or nitrate as a nitrogen source for biosynthesis can be neglected, since ammonia was present in excess during experimental period and is the preferred nitrogen source for microorganisms. Consequently, plotting $\ln([NO_2^{-1}\text{-}N] + [NO_3^{-1}\text{-}N])$ versus time gives a slope of $(\mu_{ANH4} - b_A)$ which is the effective specific growth rate of Nitrosomonas. Due to the terms neglected in equation (4-6), a deviation from straight line in the plot is expected for the first few experimental data.

For nitrite oxidation, the following equation can be derived:

$$\ln[NO_3^{-1}\text{-}N]_t = \ln \frac{\mu_{ANO2}\, X_{BANO2o}}{Y_{ANO2}(\mu_{ANO2} - b_A)} + (\mu_{ANO2} - b_A)\, t \qquad (4\text{-}7)$$

where, $[NO_3^{-1}\text{-}N]_t$ = concentration of nitrite nitrogen at t, g/m^3

Y_{ANO2} = growth yield for nitrite oxidizers, g/g

By plotting $\ln[NO_3^{-1}\text{-}N]$ versus time, a slope $(\mu_{ANO2} - b_A)$ which is the effective specific growth rate of Nitrobacter could be estimated.

Materials and Methods

Summary of Experiments

The specific maximum growth rates for Nitrosomonas and Nitrobacter were determined using laboratory fed-batch reactors as in the experiments for the half-saturation coefficients. A total of six experiments each for Nitrosomonas and for Nitrobacter were carried out.

Microorganisms

The microorganisms described in Chapter 3 were used in these experiments.

Experimental Procedures

A refrigerated wasting sludge was aerated for at least 1 hour to acclimate to room temperature of 25°C. 170 ml of the acclimated wasting sludge were added to two 2 L beakers in a water bath for temperature control along with micronutrients and 1.53 L of secondary clarifier effluent from the UFSTP. In order to neutralize acids produced from nitrification, 5 g of sodium bicarbonate were added to both beakers. The experimental apparatus was the same as in Figure 3-1. In order to avoid lack of substrate, i.e., ammonia nitrogen, and inhibition of nitrification due to high concentrations of Free Ammonia (FA), a concentration of approximately 10 g NH_4^+-N/m^3 was maintained during experiments. At the beginning of each experiment, ammonia nitrogen was provided by spikes. After the estimation of a conversion rate, a syringe pump was used. A solution of ammonium sulfate, 5000 g NH_4^+-N/m^3, was used as a source of ammonia nitrogen instead of ammonium chloride since the peak of nitrite overlapped with that of chloride in the printout of the ion chromatograph, whereas a 5000 g NO_2^--N/m^3 sodium nitrite solution was used as the source for nitrite oxidizing bacteria. Micronutrients were added as described in chapter 3. At the end of each experiment, the concentrations of MLSS in both reactors were measured.

Analytical Methods

Ammonia Nitrogen

The method described in Chapter 3 was used.

Nitrate and nitrite nitrogen

The method described in Chapter 3 was used.

Mixed Liquor Suspended Solids

The method described in Chapter 3 was used.

Results of Experiments

Experimental results for ammonia and nitrite nitrogen oxidation are shown in Tables 4-1 and 4-2, respectively. The values for the effective maximum specific growth rate of

Nitrosomonas ranged from 0.6799 day^{-1} to 0.5819 day^{-1} with an average of 0.6510 day^{-1} under conditions of a temperature of 25°C and an average pH of 7. The duration time for the experimental phase was about 3 days while the production of oxidized nitrogen was 360 gN/m^3. The results of six experiments are shown in Figures 4-1 and 4-2.

Values for the effective maximum specific growth rate of Nitrobacter ranged from 0.8741 day^{-1} to 0.7623 day^{-1} with an average of 0.8204 day^{-1} under the similar same conditions as for the Nitrosomonas experiments. The exponential phase lasted for about 3 days while production of nitrate nitrogen was about 300 gN/m^3. The results of six experiments are shown in Figures 4-3 and 4-4.

As seen from semi logarithmic plots (Figures 4-1 - 4) for all the experiments, the majority of data fit straight lines, as predicted from the theory. In determining ($\hat{\mu}_A - b_A$), only the data from the exponential phase, i.e., those lying on a straight line were used. For all experiments, the data which were used to compute the effective maximum specific growth rates gave very good correlation coefficients, $r^2 > 0.99$.

Table 4-1. Summary of experimental results for the effective specific growth rate of Nitrosomonas.

Exp. #	$\hat{\mu}_{ANH4}$-b_A 1/d	r^2	Data Points	pH	Avg. Temp° C	MLSS g/m^3
1	0.6705	0.992	10	6.8-7.2	25	200.5
2	0.6482	0.992	7	6.8-7.2	25	200.8
3	0.5819	0.993	8	6.8-7.2	25	195.6
4	0.6799	0.998	9	6.8-7.2	25	195.6
5	0.6663	0.995	10	6.8-7.2	25	210.5
6	0.6593	0.996	10	6.8-7.2	25	210.6

Average Value of $\hat{\mu}_{ANH4} - b_A$ = 0.6510 1/d
Standard Deviation = 0.0408 1/d

Table 4-2. Summary of experimental results for the effective specific growth rate of Nitrobacter.

Exp. #	μ_{ANO2}-b_A 1/d	r^2	Data Points	pH	Avg. Temp.° C	MLSS g/m^3
1	0.8169	0.998	9	6.8-7.2	25	189.4
2	0.8715	0.999	9	6.8-7.2	25	189.4
3	0.8088	0.994	8	6.8-7.2	25	185.5
4	0.8741	0.997	8	6.8-7.2	25	185.6
5	0.7623	0.991	8	6.8-7.2	25	187.8
6	0.7890	0.998	9	6.8-7.2	25	188.3

Average Value of $\mu_{ANO2} - b_A = 0.8204$ 1/d
Standard Deviation = 0.0324 1/d

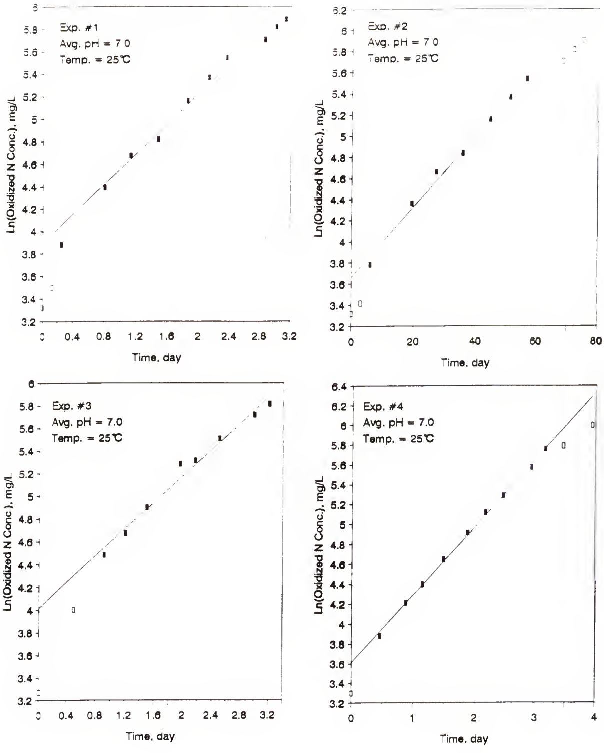

Figure 4-1. Nitritification results from experiments 1,2,3 and 4 (■: Data used for estimation).

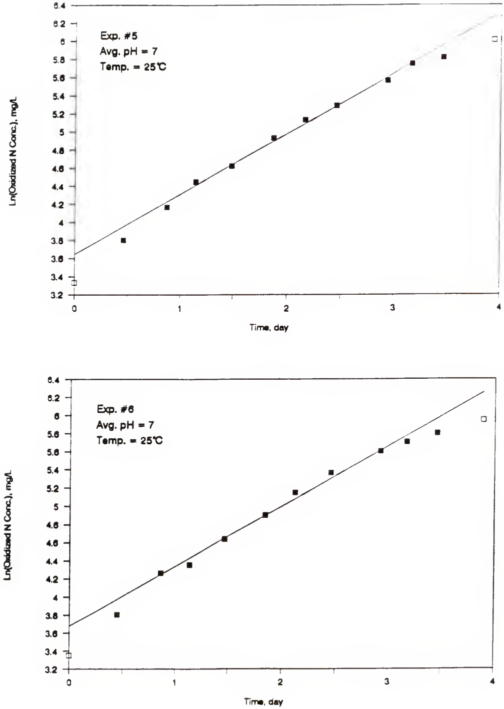

Figure 4-2. Nitritification results from experiments 5 and 6 (■: Data used for estimation).

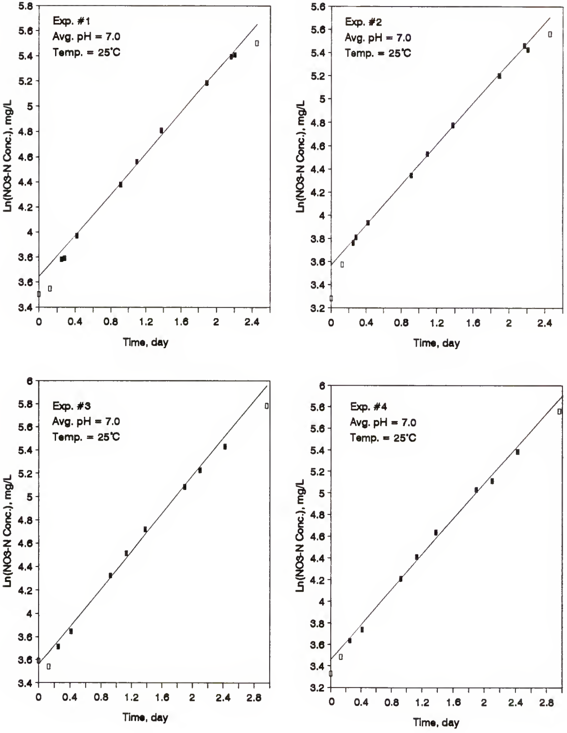

Figure 4-3. Nitratification results from experiments 1,2,3 and 4 (■: Data used for estimation).

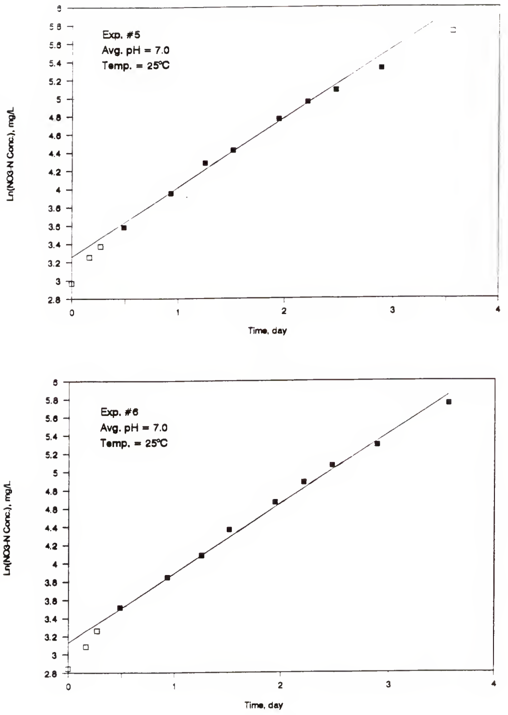

Figure 4-4. Nitratification results from experiments 5 and 6 (■: Data used for estimation).

CHAPTER 5

CONTROL OF NITRIFICATION IN CONTACT STABILIZATION PROCESS

Introduction

The contact stabilization process is a modified activated sludge system that has been used to treat domestic wastewater with less aeration tank volume compared to common activated sludge systems (Metcalf & Eddy, 1991). Although partial nitrification in the contact stabilization process was studied by several researchers (Gujer and Jenkins, 1975; Alexander, et al., 1980; Dold, et al., 1980), control strategies for nitrification were not fully investigated.

In this study, partial nitrification was evaluated by changing two operation parameters: Sludge Retention Time (SRT) and Sludge Recycle Ratio. At SRTs of 4.8 days and 6 days, three different sludge recycle ratios, i.e., 50%, 80% and 110% of influent flow rate (0.0125 m^3/day), were used to find their effects on nitrification. In order to investigate the effects of sludge recycle ratio further on nitrification, 20% and 140% of recycle ratios were added at 6 days of SRT.

Materials and Methods

Microorganisms

A mixed culture taken from a contact tank at the University of Florida Sewage Treatment Plant (UFSTP), Gainesville, Florida, was used. A phytoplankton screen, mesh size 365 μm with an opening diameter of 20 cm, was used to remove sand before inoculation, since a small diameter (1/4") Tygon tube was used in a bench-scale contact stabilization system.

Synthetic Wastewater

The wastewater in this study was assumed to have two waste streams: the effluent from a primary activated sludge system and spent nutrient solution from a hydroponic culture. Since a primary activated sludge is assumed to carry out only the oxidation of organic materials without nitrification, the effluent has high concentrations of ammonia nitrogen. Awong (1990) reported the spent nutrient solution had several sugar components, i.e., Glucose, Fructose, and Sucrose (Department of Environmental Engineering Sciences, et al, 1990).

In order to produce the same constituents in the synthetic wastewater, ammonia nitrogen and sugar components were added to the effluent from the University of Florida Sewage Treatment Plant (UFSTP). The synthetic wastewater consisted of Chemical Oxygen Demand (COD) constituents, ammonia nitrogen components and three micronutrients. Table 5-1 shows the concentration of stock solutions and the added amounts to 0.075 m^3 of effluent to make the target wastewater composition. Table 5-2 shows the constituent concentrations in synthetic wastewater after adding all components.

Experimental Procedures

A Contact Stabilization System was used to investigate nitrification in biological processes. This system had two bioreactors, the contact and reaeration tanks as shown in Figure 5-1. Two DO (Dissolved Oxygen) controller complexes were used to maintain DO concentrations at 4.0 ± 0.5 gO_2/m^3 in both reactors. DO electrode/probe (900 series, New Brunswick, Edison, NJ), DO analyzer (Model DO-40 New Brunswick, Edison, NJ), and recorder/controller (Model 305-720, Gulton Rustrack, Manchester, NH) were included in a DO controller complex.

The influent and a sludge recycle pump had computerized drive motors (Model 7550-90, Cole Parmer, Chicago, IL) and they were controlled by an IBM-compatible computer.

Table 5-1. Constituents of stock solutions.

Constituent	Concentration in stock solution	Amount per 75L in SE
Fructose	81.3 g/L	50.0 mL
Glucose	81.3 g/L	50.0 mL
Sugar	77.6 g/L	50.0 mL
Sodium Acetate	277.0 g/L	100.0mL
Ammonium Chloride	319.0 g/L	100.0mL
Ammonium Sulfate	395.0 g/L	100.0mL
Magnesium Sulfate	22.5 g/L	75.0 mL
Ferric Chloride	0.25 g/L	75.0 mL
Sodium Phosphate	33.0 g/L	75.0 mL
Sodium Carbonate (Baking Soda)		20.0 g

NOTE: SE = THE SECONDARY CLARIFIER EFFLUENT AT THE UNIVERSITY OF FLORIDA SEWAGE TREATMENT PLANT

Table 5-2. Concentrations of constituents in synthetic wastewater.

Constituents	Concentration	Unit
Biodegradable Soluble COD	347.9	mg COD/
Unbiodegradable Soluble COD	38.5	mg COD/
Ammonia Nitrogen	221.5	mg N/L
Nitrate Nitrogen	12.2	mg N/L
Alkalinity as CaCO3	2600.0	mg/L

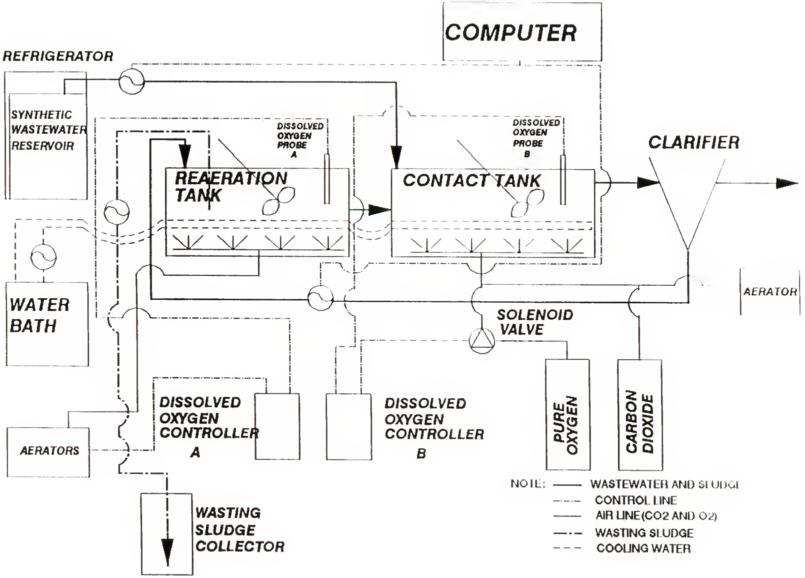

Figure 5-1. A schematic of bench-scale contact stabilization system.

Each motor had a Masterflex L/S standard pump head (Model 7016, Cole Parmer, Chicago, IL). A Masterflex pump (Model 7553-10, Cole Parmer, Chicago, IL) with a head (Model 7016, Cole Parmer, Chicago, IL) was used for a sludge wasting pump to maintain a constant SRT.

A Norprene tube was used for the influent and sludge recycle pumps since this tube could last for more than 5000 hour operation time. The sludge wasting pump used a silicone tube since this pump was not operated continuously. The sludge wasting pump was operated for 2 minutes each hour using a timer.

A solenoid valve (Grainger Model 741150115, Arlington Height, IL) was used to control the flow of oxygen from an oxygen cylinder through a rotameter (Model N062-01, Cole Parmer, Chicago, IL) since the Oxygen Uptake Rate (OUR) was too high in the contact tank to maintain a target concentration of DO by aeration only. When a fine bubble diffuser (Kondon mist-air 62503, Hayward, CA) was placed at the bottom of reactor, there was interference of the DO probe due to attachment of oxygen bubbles to the probe membrane. In order to solve this problem, a fine bubble stone diffuser along with a coarse bubble diffuser (Kondon mist-air 62501, Hayward, CA) was placed at 1/4 depth from the bottom. A coarse air bubble diffuser provided extra mixing to the contact tank. Air was supplied continuously by an air pump (Willinger Bros., Inc., Fort Lee, NJ).

In order to maintain a pH of 7.0 ± 0.2, carbon dioxide was supplied to the contact tank through a rotameter (Model N042-15, Cole Parmer, Chicago, IL). The carbon dioxide tube was inserted into the air supply tube through a needle.

A water bath and circulator (Lauda/Brinkmann, Westtowry, NY) was used to maintain a temperature of 25 ± 1 °C in both reactors. The water was circulated through 1/4" glass tubes located along the wall in each reactor.

The contact tank had a mixer (Model 65748, Precision scientific, Chicago, IL) with a Nalgene polyethylene stirrer operated at 780 rpm. An impeller was located at the bottom of the reactor. A mixer (Dayton Electric manufacture Co., Chicago, IL) with two pairs of flat type impellers rotating at 460 rpm was used to mix the contents of the reaeration tank. One pair was located at the middle and the other was placed at the bottom of the reactor, respectively.

The sludge transfer tube, 1/2" of diameter, between the reaeration tank and the contact tank was aerated through a needle to avoid anoxic conditions. Air was provided by an air pump (Willinger Bros., Inc., Fort Lee, NJ). Since a computerized system required a reliable electric power source, a battery backup system (Model BC-750, Tripplite, Chicago, IL) was used.

The influent pump with a flow rate $0.025 m^3$/day was only operated for 30 minutes in every hour since a continuous inflow was found to cause sludge bulking in the contact tank.

The sludge recycle pump was operated with different flow rates depending on the target recycle ratio. At a ratio of 110 percent, the flow rate was 9.54 ml/min. Flow rates of 6.94 ml/min and 4.34 ml/min were used for ratios of 80 and 50 percent, respectively. At recycle rates of 20 and 140 percents flow rates were 1.73 and 12.14 mL/min, respectively.

The flow rate of the sludge wasting pump was adjusted according to the target SRT, after measurement of the concentrations of Mixed Liquor Suspended Solids (MLSS) in each reactor and the effluent.

Analytical Methods

Samples from each reactor were taken to analyze the concentrations of ammonia, nitrite and nitrate nitrogen daily. Concentrations of MLSS were also measured in each reactor and the effluent daily. Soluble Chemical Oxygen Demand (SCOD) and Soluble Total Kjeldahl Nitrogen (STKN) in both reactors through a 0.45 μm membrane filter was measured weekly.

Ammonia Nitrogen

Ammonia nitrogen was analyzed using the Method described in Chapter 2.

Nitrite and Nitrate Nitrogen Two oxidized nitrogen forms, nitrite and nitrate nitrogen were measured using Ion Chromatograph (Dionex model 2000i, Sunnyvale, CA) described as in Chapter 3.

Mixed Liquor Suspended Solids (MLSS) The method described in Chapter 3 was used to measure the concentration of Mixed Liquor Suspended Solids (MLSS).

Chemical Oxygen Demand Chemical Oxygen Demand (COD) was analyzed using a COD reactor and COD vials (Model 45600C, HACH, Loveland, CO). A 2 mL sample filtered, as in the ammonia nitrogen analysis, was introduced to a vial. After 2 h digestion in a COD reactor, a digested sample was titrated against a 0.0125 M ferrous ammonium sulfate (FAS) solution. This FAS solution was standardized against a 0.025 M potassium dichromate standard solution before the titration. In case of total COD estimate of a mixed culture, a blender was used to homogenize the content before the digestion. In order to avoid the COD resulting from nitrite in a sample, an appropriate amount of sulfamic acid was added to a COD vial when a sample had nitrite (American Public Health Association et al, 1985).

Total Kjeldahl Nitrogen Total Kjeldahl Nitrogen (TKN) was measured according to NO. 00625 in Methods for

Chemical Analysis of Water and Wastes (U.S. EPA, 1979). The samples for soluble TKN were filtered as in the ammonia nitrogen analysis except for a filterate nitrate removal procedure. Since higher nitrate concentrations (10 times or higher than the TKN level) can result in low TKN values, an anion exchange resin (Rohm and Hass Co., Philadelphia, PA) was used to remove nitrates in the filtrate. The required amount of resin was calculated according to Hutton (1991).

In order to avoid nitrate interference in total TKN measurement, separation of solids by a centrifuge was adopted to measure TKN of solids since an anion exchange resin cannot be separated from solids after nitrate removal from samples. After 30 minutes of centrifugation, the supernatant having nitrate was discarded using a Pasteur pipet and ammonia-free water was filled to make the original volume (20 mL). A block digester (Model BD-40, Technicon, Tarr Town, NY) with 75 mL constricted digester tubes (Bran+Luebbe, Elmsford, NY) was used to digest samples along with a digest solution (Sulfuric acid-mercuric sulfate-potassium sulfate solution) for 1 hour at 160°C and 2 and half hours at 360°C. Organic nitrogen in sample was to convert to ammonia nitrogen after digestion procedure. Ammonia from organic nitrogen in a digested solution and inorganic ammonia nitrogen was measured using same method described in ammonia nitrogen measurement. At this analysis, a NaOH solution, however, had 0.3 mL of a 10 N NaOH solution including NaI and EDTA.

Results of Experiments

The steady-state condition was determined after reviewing a graph having six components, i.e., ammonia nitrogen, nitrite nitrogen, nitrate nitrogen and the concentrations of MLSS in each reactor at different date. Figure 5-2 shows the experimental data under operating conditions at 4.8 days of SRT with 80% of sludge recycle ratio.

The steady-state values for this experiment were summarized in Table 5-3. The difficulty in maintaining a constant temperature (25°C) in both reactors during operation caused high concentrations of suspended solids in the effluent and occasionally lengthened the time to reach a steady-state under given conditions.

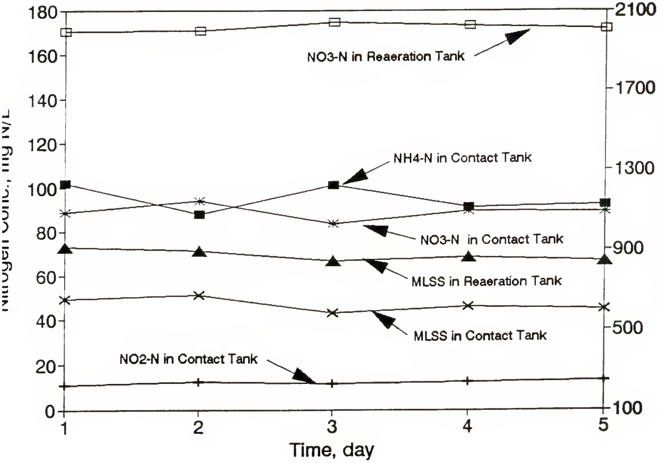

Figure 5-2. Experiment data at 4.8 days of SRT with 80% of sludge recycle ratio

Table 5-3. The steady-state concentrations of nitrogen components.

CONTACT TANK

SRT day	r = 0.2			0.5			0.8			1.1			1.4		
	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L
4.8				114.1	23	53.8	91.4	12.6	89.4	75	8	103.1			
6	204.7	3.8	23	156	2.2	66.1	119.2	5	104.8	111.1	2.8	114.1	75.7	3.08	152.5
8				143.9	2.1	87.3	112.1	1.8	111.3	118	2.1	102.3			

REAERATION TANK

SRT day	r = 0.2			0.5			0.8			1.1			1.4		
	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L
4.8				0	0	162.2	0	0	173.2	0	0	170.1			
6	0	0	209	0	0	203.8	0	0	211.4	0	0	216.7	0	0	210
8				0	0	217.4	0	0	213.6	0	0	213.6			

r = sludge recycle rate

CHAPTER 6
MODEL DEVELOPMENT AND COMPUTER SIMULATION

Introduction

The International Association on Water Pollution Research and Control (IAWPRC) task group on biological modeling developed a model for single sludge systems that accounted for eight process rates and thirteen wastewater and biological components (Henze et al, 1986). Their model divides active biomass into two components (heterotrophic and autotrophic) and nitrogen into four components (ammonia nitrogen, particulate degradable organic nitrogen, soluble degradable organic nitrogen, nitrate nitrogen). Two additional nitrogen species, particulate inert organic nitrogen and soluble inert nitrogen are recognized in the model but they do not enter the reaction equations.

In this study, the heterotrophic and autotrophic biomass components were divided into two groups, respectively, so that the model contains four biomass components. Heterotrophic biomass can be split into "nitrate reducer" and "nitrite reducer". The nitrate reducer biomass is assumed to be capable of using nitrate oxygen as a terminal electron acceptor. This division of heterotrophic biomass components need not be interpreted as a suggestion that two distinct populations of denitrifiers exist (very likely, both partial and complete denitrifiers are present). Rather, it can be interpreted as representing the respective pools of the enzyme complex, i.e., nitrate reductase and nitrite reductase, which are distributed among the heterotrophic bacteria. Autotrophic biomass was divided into ammonia oxidizers and the nitrite oxidizers. The ammonia oxidizer biomass component oxidizes ammonia to nitrite and nitrite biomass component oxidizes nitrite to nitrate.

Model Matrix

The model matrix is shown in Table 6-1. The components in the model are shown at the top of the matrix and are described on Table 6-2. The soluble components are represented by the symbol S, whereas particulate components are represented by symbol X.

Biological processes that affect the components in the model are listed in the far left column of the table. The corresponding rate expressions are given in the far right column. Process rates are denoted by the symbol ρ . An index j is assigned to each of the processes and similarly an index i is assigned to each of the components.

The elements in the matrix are the stoichiometric coefficients, v_{ij}. They signify the mass relationships between the components in the individual processes.

Table 6-1. Process kinetics and stoichiometry.

Process	1 X_I	2 X_S	3 X_{BHNO3}	4 X_{BHNO2}	5 X_{BANH4}	6 X_{BANO2}	7 X_P	8 X_{ND}	9 S_I	10 S_S	11 S_{NO2}	12 S_{NO3}	13 S_{NH4}	14 S_{ND}	15 S_{AL}	16 S_O	
1 AEROBIC GROWTH OF HETEROTROPHIC NITRATE REDUCER			1							$\frac{-1}{Y_{HNO3}}$			$-i_{XP}$		$\frac{-i_{XB}}{14}$	$\frac{-(1-Y_{HNO3})}{Y_{HNO3}}$	$\hat{\mu}_{HNO3}\left(\frac{S_S}{K_{SNO3}+S_S}\right)\left(\frac{S_O}{K_{OHNO3}+S_O}\right)X_{BHNO3}$
2 AEROBIC GROWTH OF HETEROTROPHIC NITRITE REDUCER				1						$\frac{-1}{Y_{HNO2}}$			$-i_{XP}$		$\frac{-i_{XB}}{14}$	$\frac{-(1-Y_{HNO2})}{Y_{HNO2}}$	$\hat{\mu}_{HNO2}\left(\frac{S_S}{K_{SNO2}+S_S}\right)\left(\frac{S_O}{K_{OHNO2}+S_O}\right)X_{BHNO2}$
3 ANOXIC GROWTH OF HETEROTROPHIC NITRATE REDUCER			1							$\frac{-1}{Y_{HNO3}}$	$\frac{1-Y_{HNO3}}{1.143Y_{HNO3}}$	$\frac{-(1-Y_{HNO3})}{1.143Y_{HNO3}}$	$-i_{XP}$		$\frac{-i_{XB}}{14}$		$\hat{\mu}_{HNO3}\left(\frac{S_S}{K_{SNO3}+S_S}\right)\left(\frac{K_{OHNO3}}{K_{OHNO3}+S_O}\right)\left(\frac{S_{NO3}}{K_{NO3H}+S_{NO3}}\right)\eta_{gNO3}X_{BHNO3}$
4 ANOXIC GROWTH OF HETEROTROPHIC NITRITE REDUCER				1						$\frac{-1}{Y_{HNO2}}$	$\frac{-(1-Y_{HNO2})}{1.714Y_{HNO2}}$		$-i_{XP}$		$\frac{(1-Y_{HNO2})}{14*1.714Y_{HNO2}}$ $-i_{XB}/14$		$\hat{\mu}_{HNO2}\left(\frac{S_S}{K_{SNO2}+S_S}\right)\left(\frac{K_{OHNO2}}{K_{OHNO2}+S_O}\right)\left(\frac{S_{NO2}}{K_{NO2H}+S_{NO2}}\right)\eta_{gNO2}X_{BHNO2}$
5 GROWTH OF AMMONIA OXIDIZERS					1						$\frac{1}{Y_{ANH4}}$		$-i_{XP}+$ $\frac{-1}{Y_{ANH4}}$		$\frac{-i_{XP}}{14}-\frac{1}{7Y_{ANH4}}$	$\frac{-(3.428-Y_{ANH4})}{Y_{ANH4}}$	$\hat{\mu}_{ANH4}\left(\frac{S_{NH4}}{K_{NH4A}+S_{NH4}}\right)\left(\frac{S_O}{K_{ONH4}+S_O}\right)X_{BANH4}$
6 GROWTH OF NITRITE OXIDIZERS						1					$\frac{-1}{Y_{ANO2}}$	$\frac{1}{Y_{ANO2}}$	$-i_{XP}$		$\frac{-i_{XP}}{14}$	$\frac{-(1.143-Y_{ANO2})}{Y_{ANO2}}$	$\hat{\mu}_{ANO2}\left(\frac{S_{NO2}}{K_{NO2A}+S_{NO2}}\right)\left(\frac{S_O}{K_{ONO2}+S_O}\right)X_{BANO2}$
7 DECAY OF HETEROTROPHIC NITRATE REDUCERS		$1-f_P$	-1				f_P	$i_{XB}-f_P i_{XP}$									$b_H X_{BHNO3}$
8 DECAY OF NITRITE REDUCERS		$1-f_P$		-1			f_P	$i_{XB}-f_P i_{XP}$									$b_H X_{BHNO2}$
9 DECAY OF AMMONIA OXIDIZERS		$1-f_P$			-1		f_P	$i_{XB}-f_P i_{XP}$									$b_A X_{BANH4}$
10 DECAY OF NITRITE OXIDIZERS		$1-f_P$				-1	f_P	$i_{XB}-f_P i_{XP}$									$b_A X_{BANO2}$
11 AMMONIFICATION													1	-1	1/14		$\kappa_A S_{ND} X_{BHNO3} + \kappa_A S_{ND} X_{BHNO2}$
12 HYDROLYSIS OF ENTRAPPED ORGANICS		-1								1							$K_h\left(\frac{X_S/X_{BH}}{K_X+(X_S/X_{BH})}\right)\left(\frac{S_O}{K_{OHNO3}+S_O}+\eta_h\left(\frac{K_{OHNO3}}{K_{OHNO3}+S_O}\right)\left(\frac{S_{NO3}}{K_{NO3H}+S_O}\right)+\eta_h\left(\frac{K_{OHNO2}}{K_{OHNO2}+S_O}\right)\left(\frac{S_{NO2}}{K_{NO2H}+S_{NO2}}\right)\right)X_{BH}$
13 HYDROLYSIS OF ENTRAPPED NITROGEN								-1						1			$\rho_{12}(X_{ND}/X_S)$

ρ_{12} = HYDROLYSIS OF ENTRAPPED ORGANICS PROCESS

$X_{BH} = X_{BHNO3} + X_{BHNO2}$

Table 6-2. Components of the model.

i	Symbol	Description	Units
1	X_I	Particulate inert substrate	$gCOD/m^3$
2	X_S	Particulate substrate	$gCOD/m^3$
3	$X_{B,HNO3}$	Heterotrophic biomass, nitrate reducers*	$gCOD/m^3$
4	$X_{B,HNO2}$	Heterotrophic biomass, nitrite reducers*	$gCOD/m^3$
5	$X_{B,ANH3}$	Autotrophic biomass, ammonia oxidizers*	$gCOD/m^3$
6	$X_{B,ANO2}$	Autotrophic biomass, nitrite oxidizers*	$gCOD/m^3$
7	X_{ND}	Particulate biodegradable organic nitrogen	gN/m^3
8	X_P	Particulate products from biomass decay	$gCOD/m^3$
9	S_I	Soluble inert substrate	$gCOD/m^3$
10	S_S	Soluble substrate	$gCOD/m^3$
11	S_{NO3}	Nitrate nitrogen	gN/m^3
12	S_{NO2}	Nitrite nitrogen*	gN/m^3
13	S_{NH}	Ammonia (ionized + unionized) nitrogen	gN/m^3
14	S_{ND}	Soluble biodegradable organic nitrogen	gN/m^3
15	S_{ALK}	Alkalinity (HCO_3^-)	$moles/m^3$
16	S_O	Dissolved oxygen	$gCOD/m^3$

* Proposed in this work.

The sign convention used in the matrix is positive for production and negative for consumption. The concentrations of all organic constituents, whether soluble or particulate, are given in terms of Chemical Oxygen Demand (COD). Oxygen is expressed as negative COD. The concentration of biomass and other particulates constituting the mixed liquor volatile suspended solids (MLVSS) in COD units should be multiplied in dry weight units. The concentrations of nitrogen forms are given in terms of nitrogen.

Some of the stoichiometric coefficients in the proposed model contain conversion factors relating COD units to nitrogen units. These are oxygen utilization by autotrophs and nitrate utilization, nitrite production and utilization, and alkalinity production by heterotrophs growing under anoxic conditions. The conversion factors can be derived from the half reactions for nitrogen conversion and the half reaction for reduction of molecular oxygen to water (Grady and Lim, 1980):

$$e^- + 1/2\ NO_3^- + H^+ = 1/2\ NO_2^- + 1/2\ H_2O \qquad (6\text{-}1)$$

$$e^- + 1/3\ NO_2^- + 4/3\ H^+ = 1/6\ N_2 + 2/3\ H_2O \qquad (6\text{-}2)$$

$$e^- + 4/3\ H^+ + 1/6\ NO_2^- = 1/3\ H_2O + 1/6\ NH_4^+ \qquad (6\text{-}3)$$

$$e^- + 1/4\ O_2 + H^+ = 1/2\ H_2O \qquad (6\text{-}4)$$

The derivation of each conversion factor is given below:

Oxygen Utilization by Autotrophs (coefficients 16,5 and 16,6)

The oxidation of ammonia to nitrate occurs in two steps in the proposed model. The pertinent reaction for the first step (oxidation of ammonia to nitrite) is obtained by subtracting equation (6-4) from (6-3):

$$1/6\ NH_4^+ \ +\ 1/4\ O_2 \ =\ 1/6\ NO_2^- \ +\ 1/6\ H_2O + 1/3H^+ \qquad (6\text{-}5)$$

In this reaction, 1 gram NH_4^+-N reacts with 3.428 grams O_2. The pertinent reaction for the second step (oxidation of nitrite to nitrate) is obtained by subtracting equation (6-4) from (6-1):

$$1/2\ NO_2^- \ +\ 1/4\ O_2 \ =\ 1/2\ NO_3^- \qquad (6\text{-}6)$$

In this reaction, 1 gram of NO_2^--N reacts with 1.143 grams O_2. The sum of these two coefficients is equal to the single coefficient of 4.57 that is used in the IAWPRC model to relate oxygen consumption to the growth of autotrophs.

Nitrate Utilization, Nitrite Production and Utilization, and Alkalinity Production by Heterotrophs Growing under Anoxic Conditions (coefficients 12,3; 11,3; 11,4; 15,4)

Nitrate reduction to molecular nitrogen takes place in two steps in the proposed model. The pertinent reaction for the first step is obtained by subtracting equation (6-4) from (6-1):

$$1/2\ NO_3^- \;=\; 1/2\ NO_2^- \;+\; 1/4\ O_2 \qquad (6\text{-}7)$$

This reaction shows that the quantity of electrons required to reduce 1 gram NO_3^--N to NO_2^--N is equivalent to 1.143 grams of oxygen. The pertinent reaction for the second step is obtained by subtracting equation (6-4) from (6-2):

$$1/3\ NO_2^- \;+\; 1/3\ H^+ \;=\; 1/6\ N_2 \;+\; 1/6\ H_2O \;+\; 1/4\ O_2 \qquad (6\text{-}8)$$

This reaction shows that the quantity of electrons required to reduce 1 gram NO_2^- - N to N_2 is equivalent to 1.714 grams of oxygen. The sum of these coefficients is equal to the coefficient of 2.86 that is used in the IAWPRC model to relate nitrate utilization and alkalinity production to the anoxic growth of heterotrophs.

The reaction term r_i for a given component can be written by adding up the products of the stoichiometric coefficients v_{ij} and process rates ρ_j:

$$r_i \;=\; \sum_{j=0}^{13} V_{ij}\, \rho_j \qquad (6\text{-}9)$$

Model Components

The model given by Henze et al (1986) contained 13 components, including two for biomass (heterotrophic and autotrophic) and two for inorganic nitrogen (ammonia and nitrate). The model proposed herein contains 16 components, including 4 for biomass and 3 for inorganic nitrogen (Table 6-2). The biomass and inorganic nitrogen components of the proposed model are described next.

Heterotrophic biomass is divided into nitrate reducing ($X_{B,HNO3}$) and nitrite reducing ($X_{B,HNO2}$) components. Both grow on readily degradable substrate, using oxygen as the terminal electron acceptor under aerobic conditions and nitrate or nitrite, respectively, as the terminal electron acceptors under anoxic conditions. Growth stops under anaerobic conditions, in which neither oxygen, nitrate, nor nitrite are present.

Autotroph bacteria are divided into ammonia oxidizing ($X_{B,ANH4}$) and nitrite oxidizing ($X_{B,ANO2}$) components. Ammonia nitrogen is the source of energy for the growth of the ammonia oxidizers, as well as source of nitrogen for biosynthesis of both heterotrophic and autotrophic biomass. Nitrite nitrogen is the source of energy for the growth of nitrite oxidizers. Three forms of inorganic nitrogen are considered in the proposed model: ammonia (S_{NH4}), Nitrite (S_{NO2}), and nitrate (S_{NO3}).

Model Processes

The proposed model considers thirteen processes, in comparison to the eight described by Henze et al (1990). Those differing from the original model are covered next.

Aerobic Growth of Nitrate Reducing Heterotrophs

The first process in the model (row 1 in Table 6-1) is aerobic growth of heterotrophic biomass capable of nitrate reduction. Growth occurs at the expense of readily degradable substrate (S_s) and dissolved oxygen (S_o), producing $X_{B,HNO3}$. Ammonia nitrogen (S_{NH4}) is removed from solution and incorporated in the biomass. Alkalinity (S_{ALK}) is removed in proportion to the rate of ammonia assimilation. The rate of aerobic growth is a function of the concentrations of soluble substrate and dissolved oxygen.

Aerobic Growth of Nitrite Reducing Heterotrophs

The aerobic growth of the nitrite reducing heterotrophs is shown in row 2 of Table 6-1. This process produces $X_{B,HNO2}$, but is otherwise analogous to the first process.

Anoxic Growth of Nitrate Reducing Heterotrophs

The anoxic growth of heterotrophs capable of nitrate reduction is considered in the third row of Table 6-1. Nitrate nitrogen (S_{NO3}) acts as the terminal electron acceptor in this environment. Growth occurs at the expense S_s and S_{NO3}, producing $X_{B,HNO3}$ and nitrite (S_{NO2}), S_{NH4} is assimilated for cell biosynthesis and S_{ALK} is removed in proportion to the assimilation of S_{NH4}. A correction factor, η_{GNO3}, is included in the process rate term because the maximum rate of substrate removal is found to be less under anoxic conditions than under aerobic conditions. Two switching functions control the relative rate of growth in proportion to the concentrations of S_s and S_{NO3}. A third switching function turns down anoxic growth in proportion to the concentration of S_o.

Anoxic Growth of Nitrite Reducing Heterotrophs

The anoxic growth of heterotrophic biomass capable of nitrite reduction is considered in row 4. This process is analogous to the anoxic growth of nitrate reducing heterotrophs except that S_{NO2} acts as the terminal electron acceptor in the anoxic environment and $X_{B,HNO2}$ is produced. One additional difference is that S_{ALK}, while being removed in proportion to S_{NH4} assimilation, is also produced in proportion to the growth of $X_{B,HNO2}$. A correction factor (η_{GNO2}) is used to account for the slower growth using nitrite as an electron acceptor, relative to growth with oxygen. Switching functions for S_s and S_{NO2} turn on this process whereas a switching function for S_o turns off this process.

Growth of Ammonia Oxidizers

The fifth row corresponds to the aerobic growth of ammonia oxidizers. S_{NH4} is oxidized as the energy source, consuming S_o and producing S_{NO2} and $X_{B,ANH4}$. Additional S_{NH4} is assimilated for cell biosynthesis. S_{ALK} is consumed for cell biosynthesis and by S_{NH4} oxidation. Two switching functions control the relative rate of growth in proportion to S_{NH4} and S_o.

Growth of Nitrite Oxidizers

The growth of nitrite oxidizers is considered in row 6. S_{NO2} is oxidized for energy, consuming S_o and producing S_{NO3} and $X_{B,ANO2}$. S_{NH4} is assimilated and S_{ALK} is consumed for cell biosynthesis. Two switching functions control the relative rate of growth in proportion to S_{NO2} and S_o.

Decay of Nitrate Reducing Heterotrophs

The decay of nitrate reducing heterotrophic bacteria is considered in row 7. The rate of decay is dependent on the decay coefficient, b_H and $X_{B,HNO3}$. Decay results in the loss of $X_{B,HNO3}$ and the formation of particulate products (X_P), slowly biodegradable substrate (X_s), and particulate degradable nitrogen (X_{ND}).

Decay of Heterotrophic Nitrite Denitrifiers

The decay of $X_{B,HNO2}$ is considered in row 8. This process is analogous to the decay of nitrate reducing heterotrophs.

Decay of Ammonia Oxidizers

The decay of $X_{B,ANH4}$ (row 9 of the matrix) is treated in the same fashion as the decay of heterotrophs. The decay coefficient, b_A, is different from that of the heterotrophs.

Decay of Nitrite Oxidizers

The decay of the nitrite oxidizers (row 10 of matrix) is analogous to the decay of ammonia oxidizing bacteria (Hamilton, 1991).

Ammonification of Soluble Organic Nitrogen

Conversion of soluble, degradable organic nitrogen (S_{ND}) to S_{NH4} is considered in row 11. This process is first order with respect to S_{ND} and the sum of $X_{B,HNO3}$ and $X_{B,HNO2}$. Protons are consumed on an equimolar basis with S_{NH4} produced, increasing the alkalinity of the system.

Hydrolysis of Entrapped Organics

Row 12 of the matrix considers the hydrolysis of entrapped particulate degradable (X_s) into S_s, which is available for microbial uptake. The rate of hydrolysis is dependent on the coefficient K_H and the total concentration of heterotrophic bacteria, $X_{B,HNO2}$ and $X_{B,HNO3}$. A Contois-type switching function (Contois, 1959) controls the relative rate of hydrolysis in proportion to two ratios, $X_s/X_{B,HNO2}$ and $X_s/X_{B,HNO3}$. A second function, appearing in brackets in the rate expression, controls the relative rate of hydrolysis in proportion to electron acceptor concentrations. A correction factor, η_h, is used to account for the slower rate of hydrolysis under anoxic conditions as compared to aerobic conditions.

Hydrolysis of Entrapped Organic Nitrogen

The last process in the matrix (row 13) is hydrolysis of X_{ND}, producing S_{ND}. The rate is defined by the hydrolysis reaction for X_s and the ratio of X_{ND} to X_s in the reactor.

Stoichiometric Model Parameters

The model contains seven stoichiometric parameters (Table 6-3). Three of these (f_p, i_{XB}, i_{XP}) are unchanged from the original IAWPRC model.

Table 6-3. Stoichiometric parameters for model.

Parameter	Symbol	Typical value	Unit	note
Heterotrophic yield of nitrate reducers	Y_{HNO3}	0.67	dimensionless	(a)
Heterotrophic yield of nitrite reducers	Y_{HNO2}	0.67	dimensionless	(a)
Autotrophic yield of ammonia oxidizers	Y_{ANH4}	0.212	g COD/g N	(b)
Autotrophic yield of nitrite oxidizers	Y_{ANO2}	0.029	g COD/g N	(b)
Fraction of biomass yielding particulate products	f_P	0.08	dimensionless	(c)
Mass N/mass COD in biomass	i_{XB}	0.086	g N/g COD	(c)
Mass N/mass COD in products from biomass decay	i_X	0.06	g N/g COD	(c)

(a) Assumed to be equal to the value for overall heterotrophic biomass given by Henze _el_ _al_. (1986)

(b) Based on an overall yield of 0.24 g cell COD/g NH_4^+-N oxidized (Grady and Lim, 1980)

(c) Henze et al. (1986)

The autotrophic yield, Y_A, in the IAWPRC model was the yield for the overall oxidation of ammonia nitrogen to nitrate nitrogen. The autotrophic yield in the proposed model is divided into two coefficients, one for the yield of ammonia oxidizers, Y_{ANH4}, and one for the yield of nitrite oxidizers, Y_{ANO2}. The values for these coefficients were determined from the following equations (Grady and Lim, 1980). Growth of ammonia oxidizers (Nitrosomonas):

$$55NH_4^+ + 76O_2 + 109HCO_3^- = C_5H_7O_2N + 57H_2O + 104H_2CO_3 + 54NO_2^- \quad (6\text{-}10)$$

Growth of nitrite oxidizers (Nitrobacter):

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 = C_5H_7O_2N + 3H_2O + 400NO_3^- \quad (6\text{-}11)$$

As these equations show, the yield of Nitrosomonas is 0.212 g cell COD per gram NH_4^+-N oxidized, whereas the yield of Nitrobacter is 0.029 g cell COD per gram NO_2^--N oxidized. (Note: 1 gram biomass as $C_5H_7O_2N$ equals 1.42 grams biomass as COD). The sum of these coefficients is 0.24 grams cell COD per gram NH_4^+ - N, as used in the IAWPRC model. The heterotrophic yield (Y_H) given by Henze et al, (1986) as typical was used in the model for the yield of nitrate reducing heterotrophic bacteria, Y_{HNO3}, and nitrite reducing heterotrophic bacteria, Y_{HNO2}.

Kinetic Model Parameters

The proposed model contains 22 kinetic parameters, as described in Table 6-4. Default values for these parameters from the present work are also given in the table. The parameters b_A, b_H, k_a, k_h, and k_x are unchanged from the IAWPRC model. The other parameters are discussed next.

Heterotrophic bacteria is separated into two categories: that capable of nitrate reduction and that capable of nitrite reduction. The respective maximum specific growth rates are symbolized as $\hat{\mu}_{HNO3}$ and $\hat{\mu}_{HNO2}$. The COD half-saturation coefficients are K_{SNO3} for nitrate-reducing biomass and K_{SNO2} for nitrite-reducing biomass.

The proposed model has three oxygen switching function parameters that control heterotrophic growth. The coefficient $K_{O,H}$ is the oxygen half-saturation coefficient for aerobic growth of both nitrate-reducers and nitrite-reducers. The coefficients $K_{O,HNO3}$ and $K_{O,HNO2}$ appear in the switching functions that turn down the anoxic growth of nitrate-reducers and nitrite-reducers, respectively, in proportion to S_o.

There are two nitrogen half-saturation coefficients for the anoxic growth of heterotrophic bacteria. The coefficient $K_{NO3,H}$ appears in the expression for anoxic growth of nitrate reducers, whereas the coefficient $K_{NO2,H}$ appears in the expression for anoxic growth of nitrite reducers.

Table 6-4. Kinetic parameters in the proposed model.

Parameter	Symbol	Typical value	Unit	note
Maximum specific growth rate of nitrate reducers	$\hat{\mu}_{HNO3}$	8.5	d^{-1}	(a,d)
Maximum specific growth rate of nitrite reducers	$\hat{\mu}_{HNO2}$	8.5	d^{-1}	(a,d)
COD half saturation coefficient of nitrate reducers	K_{SNO3}	20	g COD/m^3	(b)
COD half saturation coefficient of nitrite reducers	K_{SNO2}	5	g COD/m^3	(c)
Oxygen switiching function coefficient for anoxic growth of nitrate reducers	$K_{O,HNO3}$	0.25	-g COD/m^3	(b)
Oxygen switiching function coefficient for anoxic growth of nitrite reducers	$K_{O,HNO2}$	0.20	-g COD/m^3	(c)
Nitrate half-saturation coefficient for nitrate reducers	$K_{NO3,H}$	4.0	g NO_3-N/m^3	(b)
Nitrite half-saturation coefficient for nitrite reducers	$K_{NO2,H}$	0.2	g NO_2-N/m^3	(c)
Decay coefficient for heterotrophic biomass (nitrate & nitrite reducers)	b_H	1.09	d^{-1}	(b,d)

Table 6-4. Kinetic parameters in the proposed model. (continued)

Parameter	Symbol	Typical value	Unit	Notes
Correction factor anoxic growth of nitrate reducers	η_{GNO3}	0.8	dimensionless	(b)
Correction factor for anoxic growth of nitrite reducers	η_{GNO2}	0.8	dimensionless	(c)
Correction factor for hydrolysis under anoxic conditions	η_H	0.4	dimensionless	(b)
Ammonification Rate	k_a	0.11	$m^3/(g\ cell\ COD * d)$	(b,d)
Maximum specific hydrolysis rate	k_h	5.2	d^{-1}	(b,d)
Half-saturation Coefficient for hydrolysis of slowly biodegradable substrate	K_X	0.05	dimensionless	(b,d)
Maximum specific growth rate of ammonia oxidizers	$\hat{\mu}_{ANH4}$	0.55	d^{-1}	(d,e,f)
Maximum specific growth rate of nitrite oxidizers	$\hat{\mu}_{ANO2}$	0.72	d^{-1}	(d,e,f)
Ammonia half-saturation coefficient for ammonia oxidizers	$K_{NH4,A}$	0.58	g NH_4-N/m^3	(e,f)
Nitrite-half saturation coefficient for nitrite oxidizers	$K_{NO2,A}$	0.719	g NO_2-N/m^3	(e,f)
Oxygen half-saturation coefficient for ammonia oxidizers	$K_{O,NH4}$	18.0	-g COD/m^3	(g)

Table 6-4. Kinetic parameters in the proposed model. (continued)

Parameter	Symbol	Typical value	Unit	Notes
Oxygen half-saturation coefficient for nitrite oxidizers	$K_{O,NO2}$	96.0	-g COD/m^3	(g)
Decay coefficient for autotrophs (ammonia and nitrite oxidizers)	b_A	0.1	d^{-1}	(b,d)

(a) Assumed value, based on $\hat{\mu}_H$ from Henze et al. (1986)
(b) Henze et al. (1986)
(c) Hamilton (1991)
(d) Temp. = 25 °C
(e) Experiments of this research
(f) pH = 7.0
(g) Assumed value, based on model simulation

There are also two correction factors for anoxic growth of heterotrophic bacteria, η_{GNO3} and η_{GNO2}.

Autotrophic biomass is separated into ammonia oxidizers and nitrite oxidizers, each with its own maximum specific growth rate ($\hat{\mu}_{ANH4}$ and $\hat{\mu}_{ANO2}$). There are two nitrogen half-saturation coefficients for autotrophic growth: The coefficient $K_{NH4,A}$ appears in the expression for growth of ammonia oxidizers, whereas the coefficient $K_{NO2,A}$ appears in the expression for growth of nitrite oxidizers.There are also two oxygen half-saturation coefficients for autotrophic growth, $K_{O,NH4}$, and $K_{O,NO2}$.

The values for maximum specific growth rates and half-saturation coefficients for ammonia and nitrite oxidizers were evaluated in chapter 3 and chapter 4, respectively. Two oxygen half-saturation coefficients for autotrophic growth were determined by the comparisons between simulation and experiment.

Stoichiometric Coefficients

Each of the stoichiometric coefficients in Table 6-1 can be identified by its position in the matrix as mentioned earlier. For example, the coefficient, $1/Y_{HNO3}$, has the position $v_{10,1}$. This coefficient gives the rate of change in readily degradable substrate, S_s, when multiplied by process rate ρ_1. The origins of selected stoichiometric coefficients (those with conversion factors) are discussed next.

Coefficient $v_{16,5}$ and $v_{16,6}$

The coefficients $v_{16,5}$ and $v_{16,6}$ give the effect of autotrophic growth on S_o. The value 3.428 in the first coefficient represents the grams O_2 (as negative COD) required to oxidize 1 gram ammonia nitrogen to nitrite nitrogen in the absence of biosynthesis. The value of 1.143 in the second coefficient represents the quantity of O_2 (as negative COD) required to oxidize 1 gram of nitrite nitrogen to nitrate nitrogen.

Coefficient $v_{12,3}$ and $v_{12,6}$

The coefficient $v_{12,3}$ and $v_{12,6}$ convert the anoxic growth rate of nitrite reducers and growth rate of nitrite oxidizers into rates of nitrate consumption and production, respectively. Coefficient $v_{12,3}$ contains the value 1.143 which represents the quantity of electrons, in oxygen equivalents, required to reduce one gram of nitrate nitrogen to nitrite nitrogen.

Coefficients $v_{15,1}$ through $v_{15,11}$

The coefficients in column 15 give the effect of growth and ammonification processes on alkalinity. Each coefficient contains the value 14 in the denominator, which converts nitrogen quantities from grams to moles.[1] The value 1.714 in coefficient $v_{15,4}$ represents the quantity of electrons (as grams O_2) needed to reduce 1 gram nitrite nitrogen to $N_2(g)$. Finally, coefficient $v_{15,5}$ contains the value 7 in the denominator. This value accounts for the two moles of H^+ produced for each 14 grams ammonia nitrogen oxidized.

Coefficients $v_{11,3}$ and $v_{11,4}$

Coefficients $v_{11,3}$ and $v_{11,4}$ convert growth rate of the nitrate and nitrite reducers to rates of nitrite production and consumption, respectively. The value 1.143 and 1.714 were discussed previously.

Computer Simulation Results

Based on the developed process model, a computer program was written using QUICKBASIC. Applying kinetic and stoichiometric coefficients attained from literature reviews and experiments to this model, computer simulation was carried out using the experiment conditions described earlier. Since the influent pump was operated for 30 minutes each hour, a dynamic model using the fourth order Runge-Kutta method was developed. In these simulations, IBM-compatible computers were used. Table 6-5 shows steady-state nitrogen components under the operating conditions of the experiments as well as steady-state experiment data.

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[1] The second term in $v_{15,5}$ may be considered to have the multiplier 2/14.

Table 6-5. The experiment and simulation results under same operation conditions of experiments.

CONTACT TANK

		r = 0.2			0.5			0.8			1.1			1.3		
	SRT day	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L
Exp Result	4.8				114.1	23	53.8	91.4	12.6	89.4	75	8	103.1			
Sim Result					129.4	1.39	90.3	107	2.08	109.4	90	2.68	126.2			
Exp Result	8	204.7	3.8	23	156	2.2	66.1	119.2	5	104.8	111.1	2.8	114.1	75.7	3.08	152.5
Sim Result		156.3	0.7	69	110.7	2.15	110.7	127.3	1.5	93.5	88.7	2.73	127.3	79.8	3.2	133.9
Exp Result	8				143.9	2.1	87.3	112.1	1.8	111.3	118	2.1	102.3			
Sim Result					125.2	1.53	95.1	103.7	2.2	112	87.3	2.8	128.4			

REAERATION TANK

		r = 0.2			0.5			0.8			1.1			1.3		
	SRT day	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L	NH4-N mg/L	NO2-N mg/L	NO3-N mg/L
Exp Result	4.8				0	0	162.2	0	0	173.2	0	0	170.1			
Sim Result					0.3	0.4	208	0.5	0.7	212.7	0.8	1	217			
Exp Result	6	0	0	209	0	0	203.8	0	0	211.4	0	0	218.7	0	0	210
Sim Result		0.1	0.2	199.1	0.3	0.4	212.6	0.5	0.7	209.5	0.7	1	217	0.9	1.2	215.8
Exp Result	8				0	0	217.4	0	0	213.8	0	0	213.8			
Sim Result					0.3	0.4	209.7	0.5	0.6	214.4	0.7	0.9	216.6			

CHAPTER 7
EVALUATION OF THE PROPOSED MODEL

Introduction

Two different simulations were carried out to evaluate the proposed computer model. First, a contact stabilization system was simulated using the effective maximum specific growth rates and half-saturation coefficients for Nitrosomonas and Nitrobacter, estimated from fed-batch experiments. Two fed-batch systems were simulated to verify the experiments.

Statistical Analysis of Experiment and Simulation Data in Contact Stabilization Process

Alexander et al (1980) showed a good agreement between experiment and simulation data. But they did not consider nitrite nitrogen as a nitrogen component in their model.

In this study, percentages of oxidized nitrogen forms in the contact tank were compared to display the agreement between experiment and simulation data. The percentage of oxidized nitrogen forms was defined as the ratio of the sum of oxidized nitrogen to total nitrogen amount. The amount of oxidized nitrogen is represented as the sum of nitrite and nitrate nitrogens, whereas the sum of ammonia, nitrite and nitrate nitrogens is described as the total nitrogen amount.

Since the amount of organic nitrogen was too small to compare to that of inorganic nitrogen, i.e., ammonia, nitrite and nitrate nitrogen, this form of nitrogen was not considered in total nitrogen estimates. The percentage of nitrite nitrogen was expressed as the ratio of the amount of nitrite nitrogen to total nitrogen amount.

These percentages, mentioned previously, were not considered in reaeration tank since only nitrate nitrogen was in reaeration tank due to a high concentration of DO, 4 g/m^3, and longer detention time. Though a shorter detention time was anticipated at higher sludge recycle ratio, the detention time for the reaeration tank was almost twice as much as that of the contact tank.

The analysis of data from experiment and simulation can be carried out by two methods: Find a correlation coefficient and the sum of the difference between simulation and experimental data under same operation conditions. The Execustat (PWS-Kent Publishing Company, 1991) was used to estimate the correlation coefficients among percentages of oxidized nitrogen and nitrite in contact tank.

Figure 7-1 shows oxidized nitrogen percentages in contact tank at different sludge retention times. The percentage of oxidized nitrogen increases as sludge recycle ratio is higher and this trend is demonstrated regardless of SRTs.

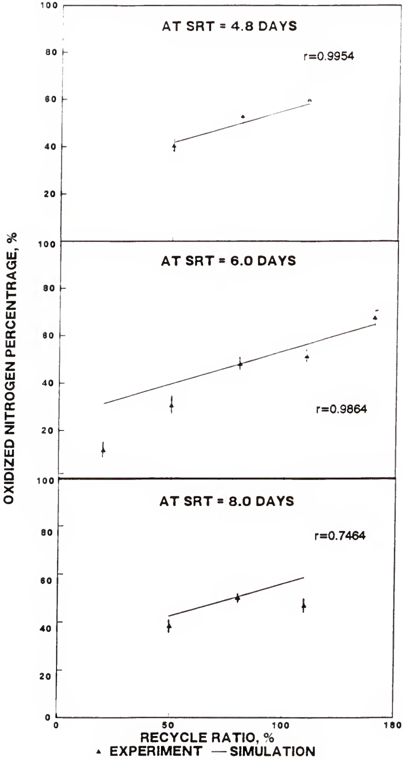


Figure 7-1. Percentages of oxidized nitrogens in contact tank according to SRTs at 50%, 80% and 110% of sludge recycle ratios.

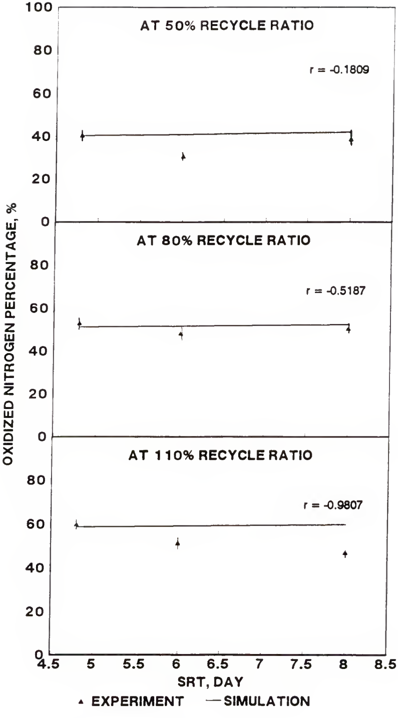


Figure 7-2. Percentages of oxidized nitrogens in contact tank according to sludge recycle ratio at 4.8, 6.0 and 8.0 days of SRTs.

The correlation coefficient, r, for each SRT is displayed on the corresponding figure. Although r is low, 0.7644, at 8.0 days of SRT, experiment and simulation data show a good correlation between recycle ratio and percentage of oxidized nitrogens.

Figure 7-2 shows the percentages of oxidized nitrogen at different SRTs and presents negative correlation coefficients between experiment and simulation data. But it is difficult to conclude that simulation and experimental data have a negative relationship since the maximum difference between two values is less than 15 percents.

Figure 7-3 displays the relationships between nitrite nitrogen percentages in contact tank and sludge recycle ratios at different SRTs. Experiment and simulation data show the opposite trend at 4.8 days of SRT. Nitrite nitrogen percentages in contact tank are generally increased with higher sludge recycle ratio at SRTs of 6.0 days and 8.0 days though they have poor correlation coefficients, -0.1560 and 0.2624, respectively.

The relationships between SRT and nitrite nitrogen percentage in contact tank were determined in Figure 7-4. As shown on these figures, the correlation coefficients, r, are all negative numbers. The maximum absolute difference between two data is 13 percent with an average value of 6.38%.

Table 7-1 has the differences between simulation and experiment in oxidized nitrogen percentage under same

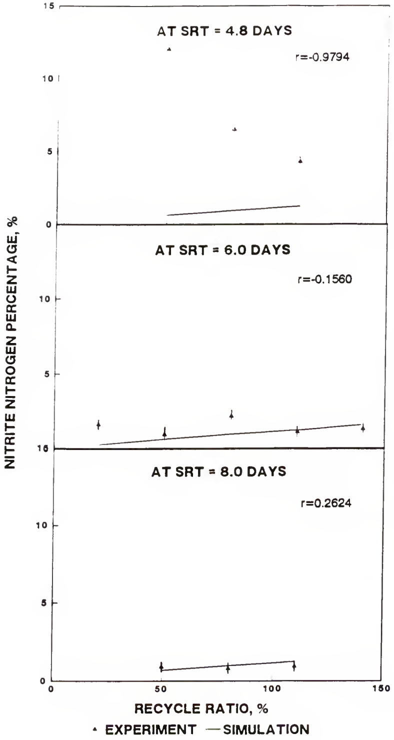


Figure 7-3. Percentages of nitrite nitrogen in contact tank according to SRTs at 50%, 80% and 110% of sludge recycle ratios.

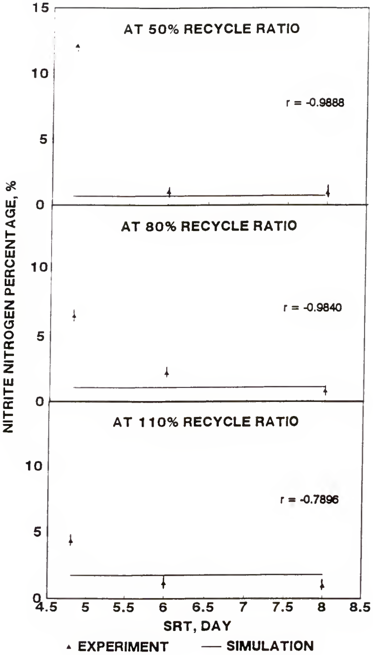


Figure 7-4. Percentages of nitrite nitrogen in contact tank according to sludge recycle ratio at 4.8, 6.0 and 8.0 days of SRTs.

Table 7-1. Percentage differences of oxidized nitrogens between simulation and experiment in contact tank.

SRT	20	50	80	110	140
day	%	%	%	%	%
4.8		11.42	5.56	3.07	
6	1.33	0.35	1.23	0.09	1.33
8		0.30	1.20	0.12	

Average = 2.36%
Standard Deviation = 3.24%

operation conditions. The difference in oxidized nitrogen percentage has an average of 6.38% with a large standard deviation, 5.65%. This large standard deviation was caused by two operation conditions such as 20% and 50% recycle ratios at 6 days of SRT.

An average in difference of oxidized nitrogens was 2.36% as shown in Table 7-2. 4.8 days of SRT caused a large standard deviation, 3.24%.

Simulation of Fed-Batch Experiments

Two series of fed-batch experiments were simulated to evaluate the proposed computer model. Exp. #7/18A and B were simulated as shown on Figure 7-5. Since wasting activated sludge from reaeration tank was used for a source of biomass in these experiments, the initial concentration of Nitrosomonas in fed-batch reactors was estimated by comparing the MLSS concentrations between the reaeration tank and the fed-batch reactor. On the date of the experiment, July 18,1991, the reaeration tank had 1200 g/m^3, whereas the fed-batch reactor had 264 g/m^3 of MLSS concentration. The initial Nitrosomonas concentration in fed-batch reactor was estimated to be 78.4 g COD/m^3 since the simulation results under same operation conditions, i.e., 8 days of SRT with 110 % recycle ratio, had 357.57 g COD/m^3.

Although the initial Nitrosomonas concentration was estimated as 78.4 g COD/m^3, the simulation in fed-batch

Table 7-2. Percentage differences of nitrite nitrogen between simulation and experiment in contact tank.

SRT	20	50	80	110	140
day	%	%	%	%	%
4.8		1.24	1.72	1.10	
6	19.26	11.87	3.76	7.94	3.41
8		4.86	2.19	12.83	

Average = 6.38%
Standard Deviation = 5.65%

reactor required 50.0 g COD/m^3 as its initial concentration to simulate experimental data. The difference of two initial concentrations could be contributed to the initial conditions of biomass in each experiment. Wasting activated sludge from contact stabilization was collected for the period of one day in a bottle in refrigerator and this refrigerated sludge was used as a source of biomass. Refrigeration may have decreased the activity of microorganisms and therefore caused the difference in initial biomass concentration.

In the case of K_{NO2A} Exp# 11/1A and B were simulated to evaluate the proposed model. On November 1, 1991, the contact stabilization system was operated at 6 days of SRT with 140% recycle ratio. Under these operation conditions, the MLSS concentration in the reaeration tank was 900 g/m^3, whereas the fed-batch reactor had 125 g/m^3. Since the simulation study under the same operation conditions showed 291.6 g COD/m^3 as the concentration of Nitrobacter, its coresponding concentration in the fed-batch reactor was estimated as 40.5 g COD/m^3. The initial concentration of Nitrobacter, 20.5 g COD/m^3, however, showed a good correspondence to the experiment. The initial acclimation of Nitrobacter to its new environment was shown in the experiment and simulation as illustrated on Figure 7-6.

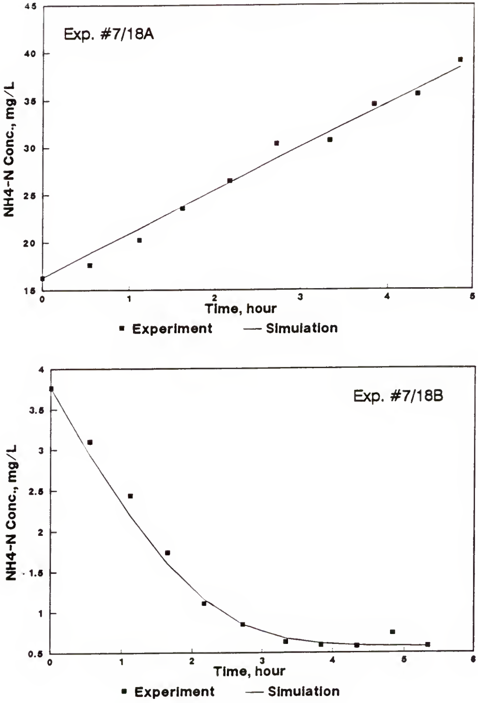


Figure 7-5. experiment and simulation data in K_{NH4A} study.

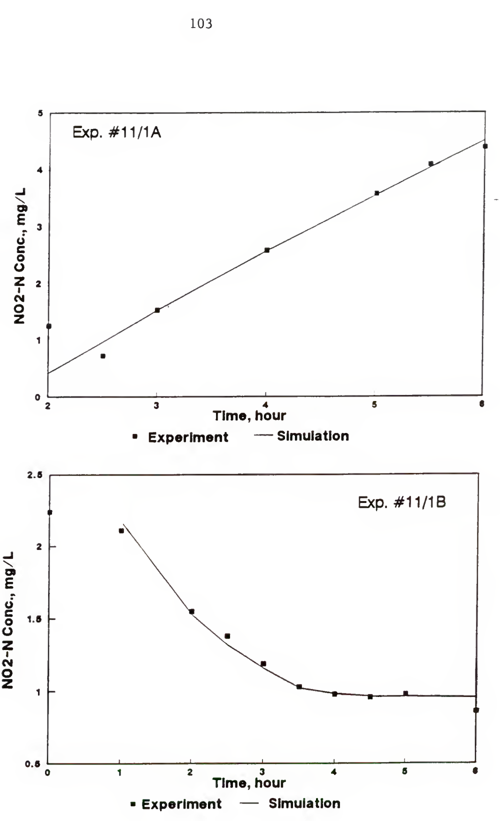


Figure 7-6. Experiment and simulation study in K_{NO2A} study.

CHAPTER 8
CONCLUSIONS

The following conclusions are drawn from this research:

1. Two half-saturation coefficients for ammonia and nitrite nitrogens were estimated as 0.58 g NH_4^+-N/m^3 and 0.72 g NO_2^--N/m^3, respectively, through fed-batch experiments.
2. The laboratory fed-batch experiments gave the effective maximum specific growth rates for ammonia and nitrite oxidizers as 0.65 d^{-1} and 0.82 d^{-1}, respectively.
3. Concentrations of near 30 g NO_2^--N/m^3 in reactor produced substrate inhibition to nitrite oxidizer, Nitrobacter, in fed-batch experiments.
4. Sludge Retention Time (SRT) did not show much impact on nitrification in the contact stabilization process.
5. The concentrations of nitrite in the contact tank showed poor correlations according to either SRT or sludge recycle ratio.
6. Experiment and simulation data showed a good correlations for the percentage of oxidized nitrogens.

7. There was poor correlation between experimental and simulation data for the percentage of nitrite nitrogen in the contact tank.
8. The percentages of nitrite nitrogen in contact tank have a poor relationship between experiment and simulation.
9. The half-saturation coefficients study showed a good correspondence between simulation and experimental data despite of the discrepancy of the initial biomass concentrations.

APPENDIX A
EXPERIMENT DATA

SRT = 4.8 DAYS WITH 110% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK									EFFLUENT	The amount of Wasting Sludge
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN N	TTKN N		MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		(mg/L)	(mL)
05-22-91	115.8	9.5	88	870				0	0	164.8	1130						38	907
05-23-91	94.9	3.9	95.2	820				0	0	173.9	1090						24	1120
05-24-91				880							1110						31	1130
05-25-91				850							710						15	1260
05-26-91				880							780						19	1210
05-28-91				890							900						31	1025
05-30-91				600							590						22	1078
05-31-91	86.9	5.8	101.4	850							770						30	1100
06-01-91	77.9	7.9	108.4	800				0	0	178.4	1000						17	1200
06-03-91	79.9	7.9	107.9	840				0	0	180.1	1040						19	1200
06-04-91	82.3	9.7	103.9	850				0	0	171.9	1130						19	1100
06-05-91	72.4	9.4	110	730				0	0	179.9	1010						12	1200
06-06-91	79.9	7	101.7	700				0	0	177.8	930						10	1250
06-07-91	74.9	9.2	107.3	730				0	0	177.2	890						12	1230
06-08-91	84.4	8.7	99.3	880				0	0	180	870						13	1180
06-07-91	73.4	7.3	107.3	740				0	0	175	900						12	1300
06-08-91	79.8	6.9	86.4	700				0	0	169.8	770						10	1250
06-08-91	79.3	7.4	100	710				0	0	171.9	880						14	1225
06-12-91	75	8	103.1	860				0	0	170.1	870						14	1180
06-13-91	80.7	7.9	86.9	890				0	0	169.9	850						14	1220

SRT = 4.8 DAYS WITH 80% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK									EFFLUENT	The amount of Wasting Sludge
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
06-14-91	102	11.1	88.6	650				0	0	170.5	910					16	1160
06-15-91	96.1	12.6	93.6	670				0	0	170.7	890					14	1160
06-16-91	101.2	11.7	93.5	580	39			0	0	174.6	940	22.5	940			16	1150
06-17-91	91.4	12.6	88.4	610				0	0	173.2	880					16	1150
06-18-91	92.4	13.2	88.2	600				0	0	171.6	940					14	1170

SRT = 4.8 DAYS WITH 50% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK									EFFLUENT	The amount of
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	Wasting Sludge
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
06-20-91	120.3	21	59.1	620				0	0	179.1	1050					17	1102
06-21-91	110.4	20.7	91.4	520				0	0	172.2	930					13	1110
06-22-91	120.1	19.5	53.7	500				0	0	165.5	900					12	1120
06-23-91	106.8	23.9	56.9	520				0	0	165.2	900					14	1110
06-24-91	114.1	23	53.9	480	25			0	0	159.5	880	25				12	1120
06-25-91	113.9	23.4	55.3	520				0	0	162.2	910					11	1150

SRT = 8 DAYS WITH 110% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK								EFFLUENT	The amount of Wasting Sludge
(mm dd yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
07-25-91	90.2	2.1	120.6	610				0	0	216.3	1210					18	840
07-26-91				800							1200					21	551
07-27-91	94.6	2.6	111.4	760				0	0	208.3	1170					15	596
07-28-91	96.1	3.1	125.5	610				0	0	217.4	1160					15	610
07-29-91	92.5			770							1160					15	611
07-30-91	104.1			610		82.75					1160			2.6		17	560
07-31-91	105.7	2.4	117.6	860				0	0	220.7	1320					23	575
08-01-91	94.57	2.8	121.6	860		89.1		0	0	210.3	1320			2.04		17	586
08-02-91	105.1	1.6	104.6	760	35.2			0	0	196.7	1280	28				21	557
08-03-91	89.5	2.3	108.9	750				0	0	185.4	1320					18	586
08-04-91	95.6	2.1	115.3	760				0	0	200	1220					15	625
08-05-91	103.9	2.5	105	730				0	0	201.6	1200					14	585
08-06-91	103.1	2.6	104.1	750				0	0	205.5	1130					14	626
08-07-91	103.6	2.3	109.4	760	27.1			0	0	208.3	1240	25.7				11	653
08-08-91	115.5	1.6	107.4	730				0	0	207	1130					11	674
08-09-91	115	2.6	98.6	740		103.4	188.6	0	0	211	1140			3.5	138.6	14	562
08-10-91	116	2.1	102.3	760				0	0	213.6	1160					22	550
08-11-91	113.1	1.6	107.9	760		114.4	183.1	0	0	217.7	1240			3.1	119.2	15	610

SRT = 8 DAYS WITH 80% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK									EFFLUENT	The amount of Wasting Sludge
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N		MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		(mg/L)	(mL)
08-20-91	111.5	2.1	130.3	910	27.1			0	0	240.2	1200	12.9					23	562
08-21-91	125.7	1.9	113.2	840				0	0	226.5	1340						36	427
08-22-91	114.6	2.1	127.5	920		119.2	213.6	0	0	230.4	1440			3.9	150.1		35	413
08-23-91	110	3.5	107.9	950				0	0	212.9	1470						35	490
08-24-91	120.1	1.5	95.9	940				0	0	201.3	1420						33	504
08-25-91	112.6	2.5	96.6	880				0	0	196.2	1380						26	543
08-26-91	126	1.9	101.3	990				0	0	205.1	1420						19	571
08-27-91	118.9	2.5	114.3	870				0	0	211.9	1200						19	549
08-28-91	113.6	2.9	114	800				0	0	212.3	1350						14	635
08-29-91	118.7	2.1	113.4	910				0	0	209.9	1240						11	654
08-30-91	119.7	2.9	107.2	770		95.1	163.3	0	0	205.9	1160			0.9	99.3		12	571
08-31-91	112.1	1.9	111.3	770				0	0	213.9	1150						19	580
09-01-91	123.9	1	109.5	930				0	0	212.9	1430						23	573

SRT = 8 DAYS WITH 50% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK								EFFLUENT	The amount of Wasting Sludge
(mm-dd-yr)	NH4 - N (mg/L)	NO2 - N (mg/L)	NO3 - N (mg/L)	MLSS (mg/L)	COD (mg/L)	STKN - N (mg/L)	TTKN - N (mg/L)	NH4 - N (mg/L)	NO2 - N (mg/L)	NO3 - N (mg/L)	MLSS (mg/L)	COD (mg/L)	MLCOD (mg/L)	STKN - N (mg/L)	TTKN - N (mg/L)	MLSS (mg/L)	(mL)
09-04-91	148.1	2	80.5	910				0	0	214.3	1550					12	646
09-05-91	154	1.9	80.9	770	34.3	138.5	213.4	0	0	220.4	1550	27.2		0.5	138.2	11	564
09-06-91	148.9	1.8	83.7	780				0	0	208.7	1400					11	648
09-07-91	149.2	1.8	81.6	690				0	0	219.5	1300					10	641
09-08-91	143.9	2.1	87.3	720				0	0	217.4	1350					9	662
09-09-91	145.9	2.1	87.3	690				0	0	217.5	1360					9	650

SRT = 6 DAYS WITH 50% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK									EFFLUENT	The amount of
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	Wasting Sludge
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
09-12-91	151.6	3.3	66.5	630				0	0	193.6	1160					15	847
09-13-91	156.6	2.4	65.6	660				0	0	195.7	1260					16	825
09-14-91	147	4.3	66.7	650				0	0	187.6	1170					24	780
09-15-91	150.3	3.6	72.3	660				0	0	202.2	1000					17	856
09-16-91	134	2.8	72	580				0	0	200.9	1070					17	821
09-17-91	143.6	2.7	66.7	580	20			0	0	204.7	970	19.7				13	866
09-18-91	157.9	2.4	83.1	580				0	0	202.1	1020					13	856
09-19-91	156	2.2	66.1	520				0	0	203.8	850					11	873
09-20-91	153	2.3	66.1	480		149.4	166	0	0	206.1	980			0.7	92.2	12	840

SRT = 6 DAYS WITH 20% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK								EFFLUENT	The amount of
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	Wasting Sludge
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
09-23-91	217.9	2.34	23.4	370				0	0	217.3	980					12	796
09-24-91	213.1	2.4	23.1	620				0	0	215.5	1180					19	817
09-25-91	210	2.9	24.4	400				0	0	210.1	1080					9	839
09-26-91	211.2	3.2	23.7	400				0	0	214.7	940					10	833
09-27-91	207.9	3.9	23.7	440	34.3			0	0	208.1	980	34.3				14	801
09-28-91	208.7	3	24	400				0	0	212.9	1080					15	797
09-29-91	204.7	3.9	23	400				0	0	209	980					10	831
09-30-91	204.5			380		209.2	237	0			980			3.1	94.2		

SRT = 6 DAYS WITH 80% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK								EFFLUENT	The amount of Wasting Sludge
(mm-dd-yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
10-06-91	120.2	4.2	98.9	920				0	0	201.5	1260					27	917
10-07-91	83.9	9.8	129.1	910				0	0	203.5	1010					22	863
10-08-91	127.3	4.7	98.8	980				0	0	206.5	940					29	875
10-09-91	112.9	8.9	103.9	720				0	0	211	1160					27	778
10-10-91	114.1	7.3	106.9	760				0	0	206.9	1300					27	782
10-11-91				980							1080					20	869
10-12-91	106			820	37.2						1080	31.5				17	830
10-13-91	117.9			700							1020					12	919
10-14-91	120.9	5.7	99.4	700				0	0	211.9	980					19	790
10-15-91	119.2	5	104.9	710				0	0	211.4	1020					17	865
10-16-91	126.2	3.9	97.9	980		129	183.5	0	0	217.9	980			1.11	74.31	15	794

SRT = 6 DAYS WITH 110% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK									EFFLUENT	The amount of Wasting Sludge
(mm dd yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	STKN - N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COD	MLCOD	STKN - N	TTKN - N	MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
10-19-91	96.2	2.4	124.7	760				0	0	214.4	910					20	880
10-20-91	106.1	2.6	116.1	660				0	0	216.8	880					11	943
10-21-91	111.1	2.8	114.1	660				0	0	216.7	900					22	799
10-22-91	113.1	2.6	117.6	660	38.6	105.4	159.4	0	0	213.5	940	34.3		2.19	64.6	16	866

SRT = 6 DAYS WITH 140% RECYCLE RATIO

DATE	CONTACT TANK							REAERATION TANK								EFFLUENT	The amount of Wasting Sludge
(mm dd yr)	NH4 - N	NO2 - N	NO3 - N	MLSS	COO	STKN N	TTKN - N	NH4 - N	NO2 - N	NO3 - N	MLSS	COO	MLCOO	STKN - N	TTKN - N	MLSS	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mL)
10-27-91	94.9	2.5	159.1	790				1.34	0	215.7	900					20	870
10-28-91	67.3	2.9	162.3	850				1.19	0	224.9	970					19	914
10-29-91	86.9	2.3	147.2	790				0.5	0	213.2	940					25	822
10-30-91	78.9	2.35	146.5	720				0	0	201	860					17	866
10-31-91	75.7	3.08	152.5	720				0	0	210	800					19	899
11-01-91	78.9	2.3	146.5	790	34.3	80.9	139.4	0	0	205.9	820	34.3		1.67	72.7	15	924

APPENDIX B
COMPUTER PROGRAM

```
Rem Program for Dynamic Simulation of a WWTP using Runge-Kutta method.
Rem Clarifier is assumed to be perfect separator
Rem Number of tanks (in series) is variable
rem Last changes : March 7, 1992
rem Define Double precision
defdbl a-h,o-z
defint i-n
rem
rem
rem
dim dkl(4),o2con(4)
dim dkla(6),eqdo(6),phi(60,61),delta(60),codin(4)
dim codeff(4),codwaste(4),dsno(4)
dim XFeed(8,48),SFeed(8,48),x(8,4),s(8,4),dnue(16,13),rate(16,3),xx(50)
dim q(48),disso2(2)

rem
common shared yanh4,yano2,yhno3,yhno2,fp,dixb,dixp,_
                 dksno3,dksno2,dkohno3,dkohno2,dkno3h,dkno2h,dknh4a,dkno2a,_
                 dkonh4,dkono2,etah,etagno3,etagno2,dmuhno3,_
                 dmuhno2,bh,dka,dkh,dkx,ba,dmuanh4,dmuano2,dnue(),dkla(),_
                 eqdo1,eqdo2,w,w1,w2,srt,x(),s(),notanks,r,_
                 disso2(),q(),eqdo(),vtotal,ihalf,XFeed(),SFeed(),delt,_
                 q,q1,q2,q3,q4,qh,rate(),v1,v2
rem
rem  input.dat contains the initial values at time t=0
rem  dyninp.dat contains time varying variables ( value at 0 and 48 th hour
rem   are same)
rem  output.dat contains daily output
rem  dynopt.dat contains dynamic output
rem
open "c:\qb87\model\sin_1.dat" for input as #1
open "c:\qb87\model\dIN48_1.dat" for input as #2
open "c:\qb87\model\outpt811.dat" for output as #5
open "c:\qb87\model\dynopt81.dat" for output as #6
rem
temp=25.0#              'temp is temperature in degree C.
pH=7.0#
rem
rem  Stoichiometric parameters :-
rem
yanh4=0.212#  : yhno3=0.67# : yhno2=0.67# : fp=0.08# : dixb=0.086#
dixp=0.06# : yano2=0.029#
rem
rem  Kinetic parameters :-
dksno3=20.0# : dkohno3=0.25# : dkno3h=4.0# : dknh4a=0.58#
dksno2=5.0# : dkohno2=0.2# : dkno2h=0.2# : dkno2a=0.719#
dkonh4=0.4#*45.0# : dkono2=0.4#*240.0#
etah=0.4# : etagno3=0.7# : etagno2=0.7#
rem
rem  Following parameters are temperature dependent :-
dmuhno3=6.0#*exp(0.0693147#*(temp-20.0#))
rem dmuhno3=5.2#
dmuhno2=6.0#*exp(.069#*(temp-15#))
rem dmuhno2=5.2#
bh     =0.62#*exp(0.1131402#*(temp-20.0#))
rem bh=0.5#
dka    =0.08#*exp(0.0693147#*(temp-20.0#))
rem dka=0.07
dkh    =3.0# *exp(0.1098612#*(temp-20.0#))
rem dkh=2.4#
dkx    =0.03#*exp(0.1098612#*(temp-20.0#))
```

```
rem dkx=0.024#
rem ba     =0.1#
ba   =0.09#*exp(0.1098612#*(temp-20.0#))
rem dmuanh4=0.7#*exp(0.1283707#*(temp-20.0#))
dmuanh4=0.551017#
rem dmuano2=((4.7*10^14)*exp((-9980)/(temp+273)))/(1+(2.05*10^-9)/(10^(-pH))+(10^(-pH))/(1.66*10^-7))
dmuano2=0.720433#
rem
rem  X => insoluble constituents:-
rem   1: inert,                    Xi        5: autotrophic biomass,  Xbanh4
rem   2: slowly biodegradable,   Xs           (Ammonia-N Oxidizing)
rem   3: heterotrophic biomass,  Xbhno3    6: autotrophic biomass,  Xbano2
rem      (Nitrate Reducing)                  (Nitrite Dxidizing)
rem   4: heterotrophic biomass,  Xbhno2    7: Particulate Product,  Xp
rem      (Nitrite Reducing)                8: organic nitrogen,     Xnd
rem
rem  S => soluble constituents:-
rem   1: inert,                    Si        5: ammonia nitrogen,     Snh4
rem   2: substrate,                Ss       6: organic nitrogen,     Snd
rem   3: nitrite-nitrogen,         Sno2     7: alkalinity,           Salk
rem   4: nirtate-nitrogen,         Sno3     8: dissolved oxygen,     So
rem
rem  i is index for constituents
rem  j is index for process
rem  k is index for tanks and streams
rem
rem  Nues are stoichiometric coeff. in matrix in Table Nitrite model
for i = 1 to 16
        for j = 1 to 13
                dnue(i,j)=0.0#
        next
next
dnue(2,7)=1.0#-fp : dnue(2,8)=dnue(2,7) : dnue(2,9)=dnue(2,7)
dnue(2,10)=dnue(2,7) : dnue(2,12)=-1.0#
dnue(3,1)=1.0# : dnue(3,3)=1.0# : dnue(3,7)=-1.0#
dnue(4,2)=1.0# : dnue(4,4)=1.0# : dnue(4,8)=-1.0#
dnue(5,5)=1.0# : dnue(5,9)=-1.0#
dnue(6,6)=1.0# : dnue(6,10)=-1.0#
dnue(7,7)=fp : dnue(7,8)=fp : dnue(7,9)=fp : dnue(7,10)=fp
dnue(8,7)=dixb-fp*dixp : dnue(8,8)=dnue(8,7) : dnue(8,9)=dnue(8,7)
dnue(8,10)=dnue(8,7) : dnue(8,13)=-1.0#
dnue(10,1)=-1.0#/yhno3 : dnue(10,2)=-1.0#/yhno2 : dnue(10,3)=-1.0#/yhno3
dnue(10,4)=-1.0#/yhno2 : dnue(10,12)=1.0#
dnue(11,3)=(1.0#-yhno3)/(1.143#*yhno3) : dnue(11,5)=1.0#/yanh4
dnue(11,4)=-(1.0#-yhno2)/(1.714#*yhno2) : dnue(11,6)=-1.0#/yano2
dnue(12,3)=-(1.0#-yhno3)/(1.143#*yhno3) : dnue(12,6)=1.0#/yano2
dnue(13,1)=-dixb : dnue(13,2)=-dixb : dnue(13,3)=-dixb : dnue(13,4)=-dixb
dnue(13,5)=-dixb-1.0#/yanh4 : dnue(13,6)=-dixb : dnue(13,11)=1.0#
dnue(14,11)=-1.0# : dnue(14,13)=1.0#
dnue(15,1)=-dixb/14.0# : dnue(15,2)=dnue(15,1) : dnue(15,3)=dnue(15,1)
dnue(15,4)=(1.0#-yhno2)/(14.0#*1.714#*yhno2)-dixb/14.0#
dnue(15,5)=-dixb/14.0#-1.0#/(7.0#*yanh4) : dnue(15,6)=-dixb/14.0#
dnue(15,11)=1.0#/14.0#
dnue(16,1)=-(1.0#-yhno3)/yhno3 : dnue(16,2)=-(1.0#-yhno2)/yhno2
dnue(16,5)=-(3.428#-yanh4)/yanh4 : dnue(16,6)=-(1.143#-yano2)/yano2


REM
Rem Define number of tanks in system (including anoxic basin)
NoTanks=2
rem define kla1,kla2 (mass transfer coeff. for O2 ) here
dkla1=0.0# : dkla2=102.0#       'per day
```

```
rem
rem define saturation DO concentration
eqdo1=7.56# : eqdo2=8.637#      'gm O2/m3
rem
disso2(1)=4.0#  :  disso2(2)=4.0#   'Dissolved O2 conc. in aeration basin
rem
rem define tank volumes here
v1=5.0# : v2=2.5#              '
rem
w=0.6#
r=1.1#
q=12.5#
srt=8.0#              ' Solid Retention Time in days
rem
rem read initial values at t=0
rem
for ii=1 to 8
        input#1,XFeed(ii,0),x(ii,1),x(ii,2)
next ii
for ii=1 to 8
        input#1,SFeed(ii,0),s(ii,1),s(ii,2)
next ii
rem
rem read dynamically varying variables
rem
for  j=0 to 24
        input#2,ihalf,q(j),XFeed(1,j),XFeed(2,j),XFeed(3,j),XFeed(4,j),XFeed(5,j),XFeed(6,j),XFeed(7,j),XFeed(8,j),_
          SFeed(1,j),SFeed(2,j),SFeed(3,j),SFeed(4,j),SFeed(5,j),SFeed(6,j),SFeed(7,j),SFeed(8,j)
next j

rem
print#5, " SRT = ";srt;" days"
print#5, " Initial values :-"
ihalf=0
imin=0
call PrintInput
rem tank 1&2 constituent concentration are mapped into array XX
rem x(k,1) & x(k,2),k=1..6 go in xx(1)..xx(6) & xx(14)..xx(19) respectively.
for i = 1 to 8
        xx(i)=x(i,1)
        xx(i+16)=x(i,2)
next i
rem s(k,1) & s(k,2),k=1..7 go in xx(7)..xx(13) & xx(20)..xx(26) respectively.
for i = 1 to 8
        xx(i+8)=s(i,1)
        xx(i+24)=s(i,2)
next i
novar=32
t=0.0#
delt=1.0#/24.0#/60.0#    'days
tmax=20.01#     'days
icode=1
call PrintParameters(icode)
call RungeKutta(novar,t,delt,tmax,xx())
close#1
close#2
close#5
close#6
end


sub PrintInput static
```

```
   print#5,"                              "
   print#5, "COMPONENT","INPUT","     TANK  1","     TANK 2"
   PRINT#5, "                                                                    "
   PRINT#5, "  Xi  ",XFeed(1,ihalf),x(1,1),x(1,2)
   PRINT#5, "  Xs  ",XFeed(2,ihalf),x(2,1),x(2,2)
   print#5, " Xbhno3 ",XFeed(3,ihalf),x(3,1),x(3,2)
   print#5, " Xbhno2",XFeed(4,ihalf),x(4,1),x(4,2)
   print#5, " Xbanh4 ",XFeed(5,ihalf),x(5,1),x(5,2)
   print#5, " Xbano2",XFeed(6,ihalf),x(6,1),x(6,2)
   print#5, " Xp  ",XFeed(7,ihalf),x(7,1),x(7,2)
   print#5, " Xnd ",XFeed(8,ihalf),x(8,1),x(8,2)
   print#5, " Si  ",SFeed(1,ihalf),s(1,1),s(1,2)
   print#5, " Ss  ",SFeed(2,ihalf),s(2,1),s(2,2)
   print#5, " Sno2 ",SFeed(3,ihalf),s(3,1),s(3,2)
   print#5, " Sno3 ",SFeed(4,ihalf),s(4,1),s(4,2)
   print#5, " Snh4 ",SFeed(5,ihalf),s(5,1),s(5,2)
   print#5, " Snd ",SFeed(6,ihalf),s(6,1),s(6,2)
   print#5, " Salk",SFeed(7,ihalf),s(7,1),s(7,2)
   print#5, " So  ",SFeed(8,ihalf),s(8,1),s(8,2)
   print#5, "                         "
   print#5, "       "
end sub


sub EvaluateFunctions(xx(1),f(1)) static
rem dim rate(16,3)
rem map composition array XX back into soluble & particulate arrays.
q1=r*q-w
q2=qh+r*q-w
q4=r*q

for k = 1 to 8
        x(k,1)=xx(k)
        x(k,2)=xx(k+16)
next k
for k = 1 to 8
        s(k,1)=xx(k+8)
        s(k,2)=xx(k+24)
next k

for i= 1 to 8
        x(i,4)=q2/q4*x(i,2)
next i
for  i= 1 to 8
        s(i,4)=s(i,2)
next i
call DetermineRates(notanks,x(),s(),rate())
for i = 1 to 8
        f(i)=((q4*x(i,4)-q1*x(i,1)-w*x(i,1))+rate(i,1)*v1)/250.0#
        f(i+8)=((q4*s(i,4)-q1*s(i,1)-w*s(i,1))+rate(i+8,1)*v1)/250.0#
        f(i+16)=((qh*XFeed(i,ihalf)+q1*x(i,1)-q2*x(i,2))+rate(i,2)*v2)/250.0#
        f(i+24)=((qh*SFeed(i,ihalf)+q1*s(i,1)-q2*s(i,2))+rate(i+8,2)*v2)/250.0#
rem print,t,q1,q2,q4
next i
 f(16)=s(8,1)-disso2(1)
rem  f(15)=(q(ihalf)*SFeed(7,ihalf)-q1*s(7,1)+r1*s(7,2)+r2*s(7,4))/v1+dkla1*(eqdo1-s(7,1))_
rem                                                        +rate(15,1)
REM  f(31)=(q1*s(7,1)-q2*s(7,2)-r1*s(7,2))/v2+dkla2*(eqdo2-s(7,2))_
REM                                                    +rate(15,2)
 f(32)=s(8,2)-disso2(2)              ' set DO in aeration basin at disso2

end sub
```

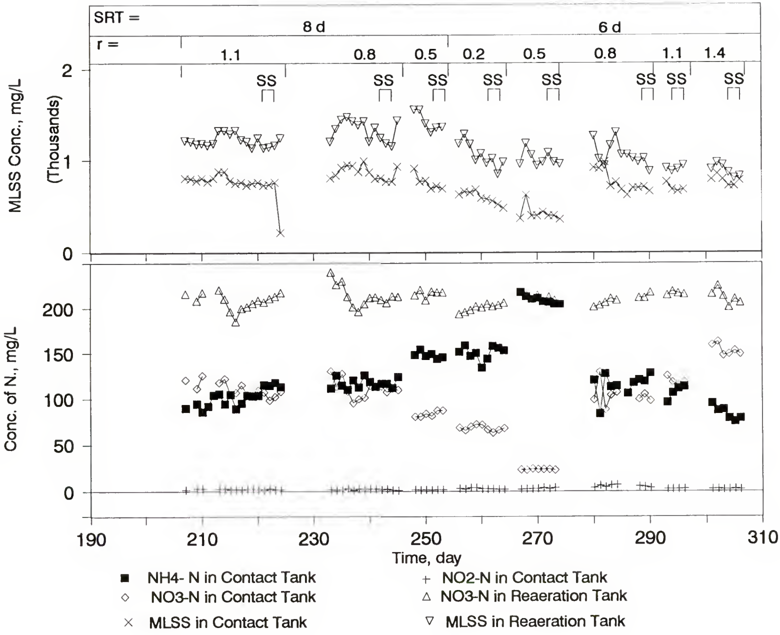
```
sub  DetermineRates(notanks,x(2),s(2),rate(2)) static
dim switch1(3),switch2(3),switch3(3),switch4(3),switch5(3),switch6(3),ro(13,3)
dim switch7(3),switch8(3),switch9(3),switch10(3),switch11(3),switch12(3)
for k = 1 to notanks
  switch1(k)=s(2,k)/(dksno3+s(2,k))
  switch2(k)=s(8,k)/(dkohno3+s(8,k))
  switch3(k)=s(2,k)/(dksno2+s(2,k))
  switch4(k)=s(8,k)/(dkohno2+s(2,k))
  switch5(k)=dkohno3/(dkohno3+s(8,k))
  switch6(k)=s(4,k)/(dkno3h+s(4,k))
  switch7(k)=dkohno2/(dkohno2+s(8,k))
  switch8(k)=s(3,k)/(dkno2h+s(3,k))
  switch9(k)=s(5,k)/(dknh4a+s(5,k))
  switch10(k)=s(8,k)/(dkonh4+s(8,k))
  switch11(k)=s(3,k)/(dkno2a+s(3,k))
  switch12(k)=s(8,k)/(dkono2+s(8,k))


  ro(1,k)=dmuhno3*switch1(k)*switch2(k)*x(3,k)
  ro(2,k)=dmuhno2*switch3(k)*switch4(k)*x(4,k)
  ro(3,k)=dmhno3*switch1(k)*switch5(k)*switch6(k)*etagno3*x(3,k)
  ro(4,k)=dmuhno2*switch3(k)*switch7(k)*switch8(k)*etagno2*x(4,k)
  ro(5,k)=dmuanh4*switch9(k)*switch10(k)*x(5,k)
  ro(6,k)=dmuano2*switch11(k)*switch12(k)*x(6,k)
  ro(7,k)=bh*x(3,k)
  ro(8,k)=bh*x(4,k)
  ro(9,k)=ba*x(5,k)
  ro(10,k)=ba*x(6,k)
  ro(11,k)=dka*s(6,k)*x(3,k)+dka*s(6,k)*x(4,k)
  ro(12,k)=dkh*x(2,k)/((x(3,k)+x(4,k))*dkx+x(2,k))*(switch2(k)+etah*switch5(k)_
              *switch6(k)+etah*switch7(k)*switch8(k))*(x(3,k)+x(4,k))
  ro(13,k)=dkh*x(8,k)/((x(3,k)+x(4,k))*dkx+x(2,k))*(switch2(k)+etah*switch5(k)_
              *switch6(k)+etah*switch7(k)*switch8(k))*(x(3,k)+x(4,k))


      for i = 1 to 16
              rate(i,k)=0.0#
              for j = 1 to 13
                      rate(i,k)=rate(i,k)+dnue(i,j)*ro(j,k)
              next j
      next i
   next k
end sub

sub  RungeKutta(n,t,delt,tmax,xx(1))  static
dim delx(60),xx1(60),xx2(60),xx3(60),dk1(60),dk2(60),dk3(60),dk4(60)
a=1.0#:b=2.0#:c=2.0#:d=1.0#
index=0
jindex = 0   'jindex accounts day
imin=0
while (t <= tmax)
rem        ihalf=int((t-int(t))*48.0#+0.001#)
            imin=int((t-int(t))*24.0#*60.0#+0.001#)
            Iflow=int((imin+30)/30)
            flowstat=Iflow mod 2%
            if flowstat = 0# then
               qh=0.0#
            else
               qh=25.0#
            end if
            call EvaluateFunctions(xx(),dk1())
```

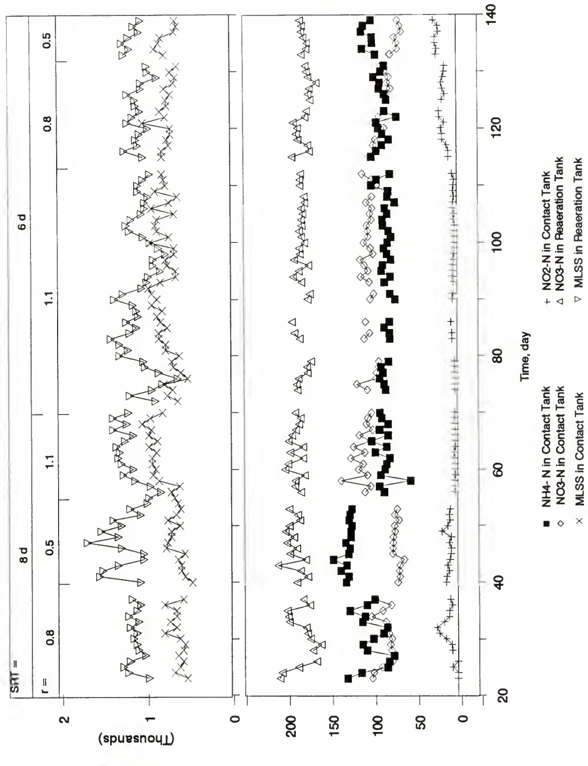
```
        for j = 1 to n
        xx1(j)=xx(j)+delt*dk1(j)
        next j
        call EvaluateFunctions(xx1(),dk2())
        for j = 1 to n
                xx2(j)=xx(j)+delt*dk2(j)
        next j
        call EvaluateFunctions(xx2(),dk3())
        for j = 1 to n
                xx3(j)=xx(j)+delt*dk3(j)
        next j
        call EvaluateFunctions(xx3(),dk4())
        for j = 1 to n
                delx(j)=delt*(a*dk1(j)+b*dk2(j)+c*dk3(j)+d*dk4(j))/6.0#
                xx(j)=xx(j)+delx(j)
        next j

rem map composition array XX back into soluble & particulate arrays.
                for k = 1 to 8
                        x(k,1)=xx(k)
                        x(k,2)=xx(k+16)
                next k
                for k = 1 to 8
                        s(k,1)=xx(k+8)
                        s(k,2)=xx(k+24)
                next k

                for i= 1 to 8
                        x(i,4)=q2/q4*x(i,2)
                        s(i,4)=s(i,2)
                next i
rem print,t,s(3,2),s(4,2),s(5,2)
            print, jindex
            print using "####.##"; t,
            print using "####.##"; qh,
            print using "#####.#"; s(3,1),
            print using "#####.#"; s(3,2),
                print using "#####.#"; s(4,1),
            print using "#####.#"; s(4,2),
                print using "#####.#"; s(5,1),
            print using "#####.#"; s(5,2)

rem following code provides dynamic output  4 times a day (with ifreq1=600)
rem for more frequent output decrease ifreq1  and vice versa
rem     if (index > 725) and (index < 735)  then
        if (index = 730) then
rem       if t- int(t+.0001#)<.0003#  then
rem     if (int(t*24.0#*60.0#+0.0001#) mod ifreq1)=0   then
rem map composition array XX back into soluble & particulate arrays.
                for k = 1 to 8
                        x(k,1)=xx(k)
                        x(k,2)=xx(k+16)
                next k
                for k = 1 to 8
                        s(k,1)=xx(k+8)
                        s(k,2)=xx(k+24)
                next k

                for i= 1 to 8
                        x(i,4)=q2/q4*x(i,2)
                        s(i,4)=s(i,2)
                next i
```

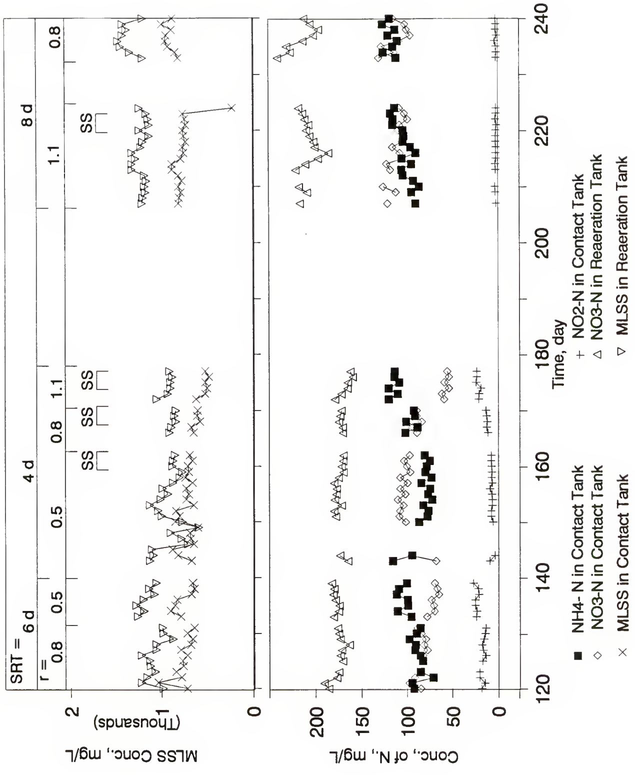
```
rem print,t,s(3,2),s(4,2),s(5,2)
                  print using "####.##"; t,
                  print using "####.##"; qh,
                  print using "#####.#"; s(3,1),
                  print using "#####.#"; s(3,2),
                        print using "#####.#"; s(4,1),
                  print using "#####.#"; s(4,2),
                        print using "#####.#"; s(5,1),
                  print using "#####.#"; s(5,2)
print#6,t,s(3,1),s(4,1),s(5,1),s(3,2),s(4,2),s(5,2)
rem call PrintOutput(t,s(),x())
rem        end if
      end if
rem  Following code prints daily output (with ifreq2=1)
rem  for less frequent output,say every 3 days, make ifreq2=3
              ifreq2=19
rem          ifq2=1400*ifreq2
              if (jindex > 0 ) then
               if (jindex mod ifreq2)=0 then
                if (index = 1439) then
rem       ifreq2=2400.0#
rem      if t- int(t+.0001#)<.0003#  then
rem       if  (int(t*2400  +0.00001#) mod ifreq2)=0  then
                         icode=2
                        call PrintParameters(icode)
                        print#5," "
                        print#5,"  "
rem              print#5," Day ";int(t+0.0001#)
                        print#5," Day ";jindex, "SRT = ";SRT, "r =";r
              call PrintInput
              end if
            end if
      end if
            t=t+delt
            index=index+1
            if (index =1440) then
             index=0
             jindex=jindex+1
rem           if (jindex = 21) then
rem            jindex = 0
rem            end if
            end if
rem         if (imin = 1440) then
rem         imin = 0
rem         end if

wend
end sub



rem sub PrintOutput(t,s(2),x(2))  static
rem print#6,t;s(3,1);s(4,1);s(5,1);s(3,2);s(4,2);s(5,2)
rem end sub


sub PrintParameters(icode) static
if (icode=1) then
     print#5, " Kinetic and Stoichiometric Parameters for Heterophic Biomass"
     print#5, "                                                              "
     print#5, " Parameter               Nitrite     Nitrate     Units"
     print#5, "                         reducer     reducer          "
```

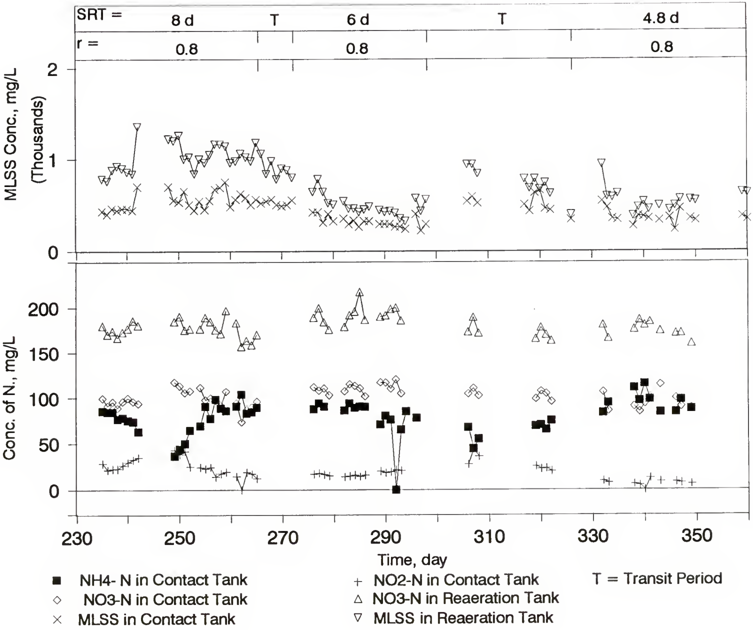
```
    print#5, "                                              "
    print#5, " Mu max        ",dmuhno2,"                 1/day"
    print#5, " Mu max                        ",dmuhno3,"1/day"
    print#5, " Ks COD        ",dksno2, "                gm COD/m3"
    print#5, " Ks COD                        ",dksno3," gm COD/m3
    print#5, " Ko O2        ",dkohno2,"                gm O2/m3"
    print#5, " Ko O2                        ",dkohno3,"gm O2/m3
    print#5, " Yield        ",yhno2,"                gm/gm"
    print#5, " Yield                       ",yhno3,"  gm/gm"
    print#5, " b decay      ",bh,"                   1/day"
    print#5, " b decay                      ",bh,"    1/day"
    print#5, " anoxic growth ",etagno2
    print#5, " factor                      ",etagno3
    print#5, " Ks NO2       ",dkno2h,"                gm N/m3 "
    print#5, " Ks NO3                       ",dkno3h," gm N/m3 "
    print#5, " Hydrolysis rate",dkh,"1/day  "
    print#5, " Hydrolys. satur.",dkx,"gm COD/gm COD"
    print#5, " ratio          "
    print#5, " Anoxic hydrolys.",etah
    print#5, " factor "
    print#5, " Ammonific. rate.",dka," m3/gmCOD/day"
    print#5, " fraction partic.",fp,"  gm COD/gm COD"
    print#5, " produced        "
    print#5, " N in biomass    ",dixb," gm N/gm COD"
    print#5, " N in particulate",dixp,"            gm N/gm COD"
    print#5, " product "
    print#5, "         "
    print#5, "         "
    print#5," "
    print#5, " Kinetic and Stoichiometric Parameters for Autotrophic Biomass"
    print#5, "                                               "
    print#5, " Parameter             Ammonia     Nitrite    Units"
    print#5, "                     Oxidizer    Oxidizer         "
    print#5, "                                               "
    print#5, " Mu max        ",dmuanh4,dmuano2,"1/day"
    print#5, " Ks NH4        ",dknh4a,"                gm N/m3 "
    print#5, " Ks NO2                    ",dkno2a,"gm N/m3 "
    print#5, " Ko NH4        ",dkonh4,"               gm N/m3 "
    print#5, " Ko NO2                    ",dkono2,"gm N/m3 "
    print#5, " Yield        ",yanh4,"                  gm/gm"
    print#5, " Yield                        ",yano2,"  gm/gm"
    print#5, " b decay      ",ba,"                     1/day"
    print#5, " b decay                      ",ba,"    1/day"

else
  print#5, "             "
  print#5, "             "
  print#5, "            Process    Description   "
  print#5, "                                      "
  print#5, " Number of Reactors       = ",2
  print#5, " Solid Retention Time     = ",srt," days"
  print#5, " Diss. O2 in Reaeation Tank= ",disso2(1),"g/m3"
  print#5, " Diss. O2 in contact tank  = ",disso2(2),"g/m3"
  print#5, " Average Flow Rate        = ",q,"m3/day"
  print#5, " Activ. sludge recyc. ratio= ",r
  print#5, " Volume of reactor 1      = ",v1,"m3"
  print#5, " Volume of reactor 2      = ",v2,"m3"
  print#5, "  "
end if
end sub
```

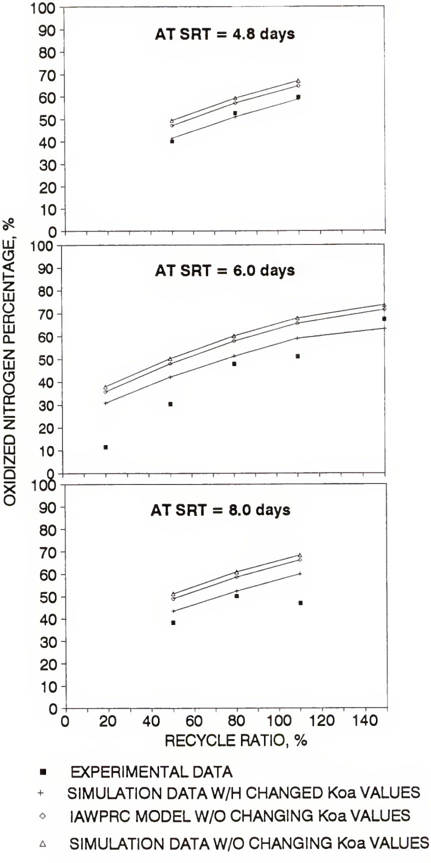
APPENDIX C
EXPERIMENT AND SIMULATION GRAPHS

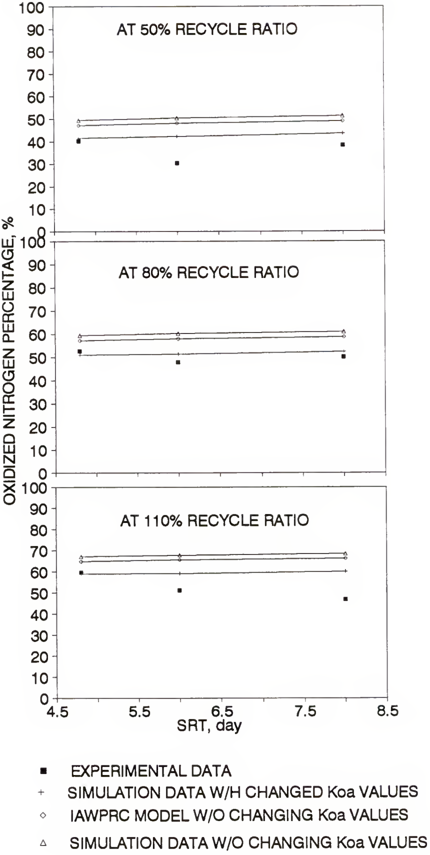

SRT =
8 d
6 d
r =
1.1
0.8
0.5
0.2
0.5
0.8
1.1
1.4
SS
MLSS Conc., mg/L
(Thousands)
2
1
0
Conc. of N., mg/L
200
150
100
50
0
190
210
230
250
270
290
310
Time, day
■ NH4- N in Contact Tank
◇ NO3-N in Contact Tank
× MLSS in Contact Tank
+ NO2-N in Contact Tank
△ NO3-N in Reaeration Tank
▽ MLSS in Reaeration Tank


SRT =
8 d
6 d
r =
0.8
0.5
1.1
1.1
0.8
0.5
MLSS Conc., mg/L
(Thousands)
0
1
2
Conc., of N., mg/L
0
50
100
150
200
Time, day
20
40
60
80
100
120
140
NH4- N in Contact Tank
NO3-N in Contact Tank
MLSS in Contact Tank
NO2-N in Contact Tank
NO3-N in Reaeration Tank
MLSS in Reaeration Tank


SRT =
6 d
4 d
8 d
r =
0.8
0.5
0.5
0.8
1.1
1.1
0.8
SS
SS
SS
SS
MLSS Conc., mg/L
(Thousands)
2
1
0
Conc., of N., mg/L
200
150
100
50
0
120
140
160
180
200
220
240
Time, day
NH4- N in Contact Tank
NO3-N in Contact Tank
MLSS in Contact Tank
NO2-N in Contact Tank
NO3-N in Reaeration Tank
MLSS in Reaeration Tank


SRT =
8 d
T
6 d
T
4.8 d
r =
0.8
0.8
0.8
MLSS Conc., mg/L (Thousands)
2
1
0
Conc. of N., mg/L
200
150
100
50
0
230
250
270
290
310
330
350
Time, day
■ NH4- N in Contact Tank
◇ NO3-N in Contact Tank
× MLSS in Contact Tank
+ NO2-N in Contact Tank
△ NO3-N in Reaeration Tank
▽ MLSS in Reaeration Tank
T = Transit Period


AT SRT = 4.8 days
AT SRT = 6.0 days
AT SRT = 8.0 days
OXIDIZED NITROGEN PERCENTAGE, %
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
RECYCLE RATIO, %
■ EXPERIMENTAL DATA
+ SIMULATION DATA W/H CHANGED Koa VALUES
◇ IAWPRC MODEL W/O CHANGING Koa VALUES
△ SIMULATION DATA W/O CHANGING Koa VALUES


AT 50% RECYCLE RATIO
AT 80% RECYCLE RATIO
AT 110% RECYCLE RATIO
OXIDIZED NITROGEN PERCENTAGE, %
0
10
20
30
40
50
60
70
80
90
100
4.5
5.5
6.5
7.5
8.5
SRT, day
■ EXPERIMENTAL DATA
+ SIMULATION DATA W/H CHANGED Koa VALUES
◇ IAWPRC MODEL W/O CHANGING Koa VALUES
△ SIMULATION DATA W/O CHANGING Koa VALUES

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BIOGRAPHICAL SKETCH

Byonghi Lee was born August 3, 1961, in Seoul, KOREA. He received his Bachelor of Science degree in environmental engineering from the Seoul City University in 1980. Following graduation, he entered the Graduate School in the Seoul National University and earned his Master of Engineering degree, in environmental engineering, in 1986. He spent six months in the Third Army Academic School, Yong-Chun, Korea, to become a Korean Army Second Lieutenant. After finishing his training, he worked at Kolon Engineering, Inc., Seoul, Korea, as a wastewater engineer.

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Byonghi Lee has been a member of Water Environment Federation since 1984.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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August, 1992

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